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POWER QUALITY ASPECTS OF VARIABLE SPEED DRIVES

Report No 90-302-K

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ABSTRACT

Power Quality aspects of Variable Speed Drives (VSDs) are summarized. The VSDs are considered as both a producer and as a victim of power line disturbances. The focus is on harmonics, although other disturbances have been identified. Applicable standards and solutions are given. Areas for future study are presented. The Appendix provides a detailed report which includes a comprehensive list of references.

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POWER QUALITY ASPECTS OF VARIABLE SPEED DRIVES

1. *Introduction*

Variable Speed Drives (VSDs) offer an efficient and cost effective method of controlling both ac and dc motors, providing industry with the opportunity to save energy and to reduce operating and maintenance costs. VSD technology uses solid-state switching devices to modify the incoming ac power in order to meet the motor's voltage and frequency control requirements. The switching injects disturbances into the supply system that can affect other equipment. On the other hand the VSD may be susceptible to the same or other types of disturbances. These considerations are Power Quality issues. This report addresses the Power Quality Aspects of VSDs.

The project was performed by the Electrical Research Department for Technical Services & Support Department of Program Support & Services Division, Energy Management Branch. The Electrical Engineering Consociates, a consultant group at the University of Toronto, performed a literature study on the subject under contract to the Electrical Research Department. The scope was to provide both a qualitative and quantitative description of the Power Quality aspects of VSDs. The focus was on harmonics. Other types of disturbances and future areas of research relevant to the control of power quality were also identified. An edited version of the consultant's report is reproduced in the Appendix. This report gives a brief review of the Power Quality aspects of VSDs based primarily on the contents of the consultant's report. For detailed information refer to the Appendix.

2. *Types of Variable Speed Drives*

Electric Variable Speed Drives can be classified as either ac or dc. There are several ac and dc drive configurations summarized in Table 1.

Table 1. AC and DC Drive Configurations

Type of Drive	Configuration	Classification	Application
AC Drive	AC/DC/AC	Square-wave voltage-source inverter (VSI), Square-wave current-source inverter (CSI), Pulse-width-modulation (PWM) VSI, Pulse-width-modulation (PWM) CSI.	Squirrel-cage/wound rotor induction machines and synchronous machines.
	AC/AC	Cycloconverter, Stator-voltage controller, Scherbius drive.	
DC Drive	AC/DC	Converter (Controlled Rectifier)	Separately excited dc machines.
	AC/DC/DC	Converter-chopper	

3. *General Power Quality Aspects of VSDs*

VSDs can be considered as both a producer of disturbances and as a victim of disturbances:

As a producer of disturbances, VSDs generate harmonics and line voltage notches that can disturb equipment on the same load distribution system and the utility supply system.

As a victim of disturbances, VSDs may be susceptible to harmonics and line voltage notches as well as other types of power line disturbances such as voltage sags and swells and transient surges that may be present on the incoming supply.

4. *Producer of Disturbances*

Limits on Harmonics

The most serious concern is to maintain acceptable levels of harmonics that the VSD injects into the plant distribution system and the utility system. There are no stipulated limits on the equipment itself. The limits are specified on the allowable voltage distortion on the plant distribution system (IEEE Std 519 [1]) or the supply system (Ontario Hydro limits [2]). These limits are given in Table 2 below.

Table 2. Harmonic Limits

Where the Limits Apply	Applicable Standard	Voltage Distortion THD	
Utility Distribution Supply System	Ontario Hydro Administrative Branch Procedure 2	Dedicated Feeder[1]	5 %
		General Feeder	3 %
Customer Low-Voltage System	IEEE Standard 519 -1981	Dedicated System[2]	10 %
		General System	5 %
Manufacturer Low-Voltage Equipment	None	None	

Notes: 1. A dedicated feeder is one that feeds only one customer.
2. A dedicated system is one that services only loads not affected by voltage distortion.

Harmonic Control Measures

It is up to the customer to recognize the potential problem and take appropriate action. This usually involves the installation of passive filters to reduce the harmonics to acceptable levels. Other techniques are summarized in Table 3 and are briefly described as follows.

Most drive applications use a conventional AC/DC converter. This consists of a line-commutated, 6-pulse thyristor bridge. This design is simple but has two major disadvantages: it generates substantial harmonics and it reflects a lagging power factor.

When shunt capacitors are installed to improve the power factor, the harmonic conditions may be exacerbated by a parallel resonance between the capacitance and the system inductance [3]. A common solution is to install reactor-tuned capacitors to force the resonance to occur at a frequency of about 240 Hz which is below the converter characteristic harmonics which start at 300 Hz.

The characteristic harmonics are of orders 5,7, 11,13 and 17,19 etc. A 12-pulse bridge significantly reduces the harmonics, eliminating orders 5,7 and 17,19. Such a converter consists of two 6 pulse converters in parallel combined with a 30° phase shift in the ac voltage. The increased transformer costs (you now require two transformers) make this less attractive for higher power applications.

The PWM AC/DC converter is a relatively new but mature technology that overcomes the disadvantages of the conventional technology. Forced-commutation uses gate turn-off (GTO) power devices to shape the current and eliminate the 5^{th} and 7^{th} harmonics. It is also attractive because it provides almost unity power factor. For low-power applications the GTO is comparable to the conventional thyristor or SCR in cost and reliability. At higher power levels this is no longer true. PWM AC/DC converters are not yet widely used in industry. The industry is basically comfortable with the old but proven technology and is reluctant to change.

The most popular control measure for AC/DC converter harmonics is the use of passive filters. Nevertheless, filters are not installed as a rule and are usually applied after the fact as a fix rather than as a preventive control measure.

The cycloconverter is becoming popular in high-power motor drive applications such as gearless mills. The harmonics from these AC/AC converters vary with motor speed and are difficult to suppress using passive filters. Active filters that track changes in drive harmonics offer an attractive solution. However, active filters are relatively new and their practicality is not yet fully understood.

Table 3. Harmonics From Common VSD Configurations

Drive Type	Configuration	Theoretical Harmonic Orders	Typical Harmonics	Control Measures to Reduce Harmonics		
AC/DC	6-pulse converter	$6k\pm1$	5,7,11,13 etc	Passive filters tuned and low pass	12-pulse	PWM converter
	12-pulse converter	$12k\pm1$	11,13 etc	Passive filters tuned and low pass		
	PWM converter	Varies with pulse width	11,13 etc plus high frequencies	Low pass filter		
AC/AC	Cycloconverter	$(6k\pm1)\pm6nf_o/f_1$	Subharmonics plus 5,7,11,13 etc plus non-integers	Active filters		

Notes: p is the pulse number; k is an integer 1,2, etc; n is an integer 0,1,2 etc; f_1 is the fundamental frequency; f_o is the output frequency

Line Voltage Notches

Limits on line voltage notching and design practices for minimizing line notching effects are given in IEEE Std 519 [1].

5. *Victim of Disturbances*

Most of the concern has focused on the VSD as a source of ac line current harmonics and voltage notches. There is also a growing concern with the effects of power system disturbances on drive performance.

Effects on Various Drive Configurations

The most widely used VSDs include AC/DC converter dc drives, AC/DC/DC converter-chopper dc drives and AC/DC/AC converter-inverter ac drives (see Table 1). These drives all have an AC/DC converter at the front-end. At the output of the converter there is a dc link. The dc link consists of a large inductor and/or capacitor that buffers the actual motor drive from the power system disturbances. Therefore, the major impact of power-system disturbances is on the AC/DC converter and not on the motor drive itself. The most serious impact is on the control signals for the power switching devices (Thyristor or SCR and GTO).

The AC/AC converter connects the power system directly to the motor drive without an intervening buffer. Therefore, this type of drive such as the cycloconverter is more vulnerable to power system disturbances than the above drives.

Immunity Requirements for the Operation of VSDs

Most VSDs use phase-controlled converters at the front-end. The control signals for firing the power switching devices in the converter rely on the zero-crossings of the power-system voltage waveform. Power system voltage disturbances may lead to misfiring or commutation failure. Generally, harmonic conditions are not severe enough to cause commutation failure. Subcycle voltage dips such as those introduced by capacitor switching may, under severe conditions, result in commutation failure followed by tripping of the drive [4].

ANSI/NEMA Standard No ICS 1-1978 [5] makes a general recommendation to call unusual non-sinusoidal supply conditions to the manufacturer's attention but gives no limits. IEEE Std-519 gives recommended harmonic operating conditions that might be used as a guide to specify the VSD requirements. IEEE Std-597-1983 [6] specifies requirements for the operation of thyristor-controlled dc drives subject to other types of voltage waveform disturbances such as repetitive peak deviations, subcycle dips and transient overvoltages. For critical drive applications the standard recommends that performance requirements for severe subcycle voltage dips should be jointly reviewed between the customer and the manufacturer.

6. *VSD Power Quality Research*

Improved analytical tools are required to properly evaluate and control the effects of harmonics and other disturbances injected by VSDs into the supply system as well as the effects of supply system disturbances on VSD performance. Several areas for further research to address these needs are identified and detailed in the Appendix. These include the development of a general computational package for power quality assessment, design and analysis of passive and active filters for controlling drive harmonics, and analysis of effects of new drive configurations on power quality.

The Electrical Research Department has already initiated a project in cooperation with Ryerson Polytechnical Institute to develop a PC-based computer program to perform a detailed Power Quality analysis of VSDs for end-use applications. The program will predict the impact of drive harmonics within the customer plant and on neighbouring customers at the point-of-common coupling. It will also evaluate the effects of power system harmonics on drive performance. An enhanced version will allow the analysis of other types of conversion systems. The complete package will be a powerful and flexible analytical and predictive tool that will prove invaluable to customers, utilities and private consultants.

Power Quality aspects of Variable Speed Drives (VSDs) have been summarized. Details are given in the Appendix.

There is a growing concern over Power Quality issues in the application of VSDs. Consideration should be given to the effects of disturbances generated by the VSDs on the power system and also to the effects of power system disturbances on the VSD performance.

8. *Acknowledgements*

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References

[1] IEEE Std 519-1981, "IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters."

[2] Ontario Hydro Regions Branch Administrative Procedure 2, "Controlling Propagation of Harmonics into the DES by Customers," OOOH, Ser. 2.6, Sec. 6.3, September 1983.

[3] G.K. Hatanaka, "Lindsay Hydro - Trent Rubber Harmonic Investigation," Ontario Hydro Research Report No 89-104-K.

[4] E.P Dick, "Review of Capacitor Switching Effects on Power Quality," Ontario Hydro Research Report No 88-239-K.

[5] ANSI/NEMA Standards Publication/No. ICS 1-1978, "General Standards for Industrial Control and Systems."

[6] IEEE Std 597-1983, "Practices and Requirements for General Purpose Thyristor DC Drives."

APPENDIX

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POWER QUALITY ASPECTS OF VARIABLE SPEED DRIVES

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TABLE OF CONTENTS

INTRODUCTION

1 PERFORMANCE ASPECTS OF VARIABLE SPEED DRIVES

- 1.1 Variable Speed Drives
- 1.2 VSDs and Power Quality
- 1.3 Drive Disturbance Limits

2 ASSESSMENT OF HARMONICS FROM VARIABLE SPEED DRIVES

- 2.1 Steady-State Symmetrical Drive Operations
- 2.2 Steady-State Unsymmetrical Operations
- 2.3 Transient Operations
- 2.4 Harmonic Disturbance from Multiple Drives
  - 2.4.1 Fixed Amplitude from Multiple Phases
  - 2.4.2 Random Amplitude and Random Phases

3 IMPACTS OF SYSTEM DISTURBANCES ON VARIABLE SPEED DRIVES

- 3.1 Drive Configurations and Disturbances
- 3.2 Severe Supply Voltage Dip
- 3.3 Supply Voltage Unbalance
- 3.4 Harmonic Disturbances in Supply System

4. CONTROL OF HARMONICS FROM DRIVES

- 4.1 Voltage Harmonics and Notches from Drives
- 4.2 Multiphasing of Drive Converters
- 4.3 Pulse-Width-Modulation (PWM) Control
  - 4.3.1 PWM Voltage-Output Converter
  - 4.3.2 PWM Current-Output Converter
- 4.4 Passive Power Filters
- 4.5 Active Power Filters

5. POWER QUALITY CONTROL RESEARCH

- 5.1 Power Quality Computational Package
- 5.2 Analysis of New Drive Configurations and Controls
- 5.3 Optimal Design of Passive Power Filters
- 5.4 Analysis and Design of Active Power Filters
- 5.5 Analysis of Drive Systems under Non-Ideal Operating Conditions
- 5.6 Analysis of Local Power Systems with Multiple Drives and Other Harmonic Sources
- 5.7 Analysis of Reactive Power Compensation and Drive Systems

6. CONCLUSIONS

INTRODUCTION

Static power-converter drives provide efficient speed control of electric machines with high performance compared to conventional drives. This leads to a wide range of converter-drive applications for both dc and ac machines of various ratings. These drives, however, may alter the sinusoidal nature of the input ac current. This results in the flow of harmonic currents into the power system. These harmonic currents and associated harmonic voltages can cause errors in metering, malfunction of utility relays, poor power factor, and interference with communication circuits and other highly sensitive electronic equipment. The harmonics can excite parallel resonances between the power factor capacitors and the inductive reactance of the power system. This may result in large oscillating currents and high harmonic voltages. Excessive conditions can cause equipment-insulation failure, premature capacitor failures, and excessive operation of protective equipment.

As applications of converter drives grow yearly, the level of harmonic pollution injected from these drives into the power system increases. These drive harmonic disturbances must be controlled effectively to maintain the quality of power on the power system. The converter drives can themselves be sensitive to disturbances on the power system.

This report was prepared by the Electrical Engineering Consociates, a consultant group, for the Ontario Hydro Research Division under a contract to study the "Power Quality Aspects of Variable Speed Drives". The project was undertaken to support utility initiatives that promote the application of VSDs in industry. A better understanding of the Power Quality aspects of VSDs will help customers apply VSDs more efficiently and reliably without jeopardizing the quality of the supply system. Further research in related areas will help to avoid or resolve power quality problems and encourage the application fo VSDs.

The report provides both a qualitative and quantitative understanding of power quality aspects of variable speed drives for both dc and ac machines. It also describes the impacts of power system disturbances on variable speed drives. Finally, it identifies several future research areas relating to the control of power quality.

1. PERFORMANCE ASPECTS OF VARIABLE SPEED DRIVES

This chapter describes the performance aspects of variable speed drives (VSDs) which may affect the quality of the supply. A brief comparison of various machine drives and their susceptibility to power system disturbances are also given in this section.

General Power Quality requirements for converters are recommended by IEEE Standard 519 [1] which is currently under revision [2]. There are no specified standard limits on the performance of VSDs or converters. IEEE Standard 519 is a guideline that recommends acceptance levels of disturbances on the power system. For a simple Power Quality analysis, the static converter drive can be treated as a harmonic-current generator. Harmonic currents injected from the drive converters through the supply impedance will result in voltage harmonics. These harmonics may affect other sensitive electronic equipment connected to the same power system. The drive converters also generate notches on the supply voltages at the point of common coupling and may also cause voltage flicker. Four limits of converter-drive disturbances that are considered acceptable on the power system are discussed in this section.

1.1 Variable Speed Drives

Electric variable speed drives are classified into ac and dc drives.

AC Drives

Basic ac drive configurations are AC/DC/AC converter-inverter drives and AC/AC converter drives. According to different drive controls and circuits, AC/DC/AC drives can further be classified into: Square-wave voltage-source inverter, Square-wave current-source inverter, Pulse-width-modulation voltage-source inverter, Pulse-width-modulation current-source inverter, and Kramer drive. Similarly, AC/AC drives can be divided into: Stator-voltage controller, Cycloconverter, and Scherbius drive. The configurations of these drives are shown in Chapter 2. These drives are used to control squirrel-cage / wound-rotor induction machines and synchronous machines.

DC Drives

Basic dc drive configurations are AC/DC converter drives and AC/DC/DC converter-chopper drives. These drives are usually employed to control separately excited dc machines.

1.2 VSDs and Power Quality

Drive Harmonics

Most machine drives use a conventional 6 pulse AC/DC converter. The rms value of all current harmonics generated by this type of converter under ideal operating conditions would be more than 20% of the fundamental line current. These drive harmonics will be detailed in Chapter 2.

Recently, several conversion schemes have been proposed to reduce these harmonics. In particular, the pulse-width-modulation (PWM) AC/DC converter offers an attractive solution. Though this new development has not been widely used in the industry, it may become more popular in the near future. Typical configurations of PWM converters are detailed in Chapter 4.

Machine drives using direct AC/AC converters generate increased levels of harmonics (see Chapter 2). Typically, cycloconverters generate harmonics of more than 30% of the fundamental rms current. These harmonics vary with the output frequency or machine speed and are difficult to suppress. A recent development in active power filters discussed in Chapter 4 may offer good control of these harmonics.

Drive Susceptibility

Certain drive converters are sensitive to the quality of power. Typically, when a 6-pulse AC/DC converter at the drive input operates in the inverting mode, the converter is vulnerable to particular power-system disturbances such as a supply-voltage dip or supply unbalance. Similarly, PWM converters may be also sensitive to the supply disturbances. Their harmonic susceptibility needs further investigation. A brief study of susceptibility of machine drives is reported in Chapter 3.

1.3 Drive Disturbance Limits

Voltage Distortion Limits

The voltage distortion at the point of common coupling will depend on the amount of harmonic current flowing through the supply impedance from the drive converter. For variable speed drives having a AC/DC converter connected to the supply system, the input harmonic currents can be approximated [1] as:

$$I_h = I_1/h \tag{1.1}$$

where I_1 is the fundamental and h is the order of the harmonic. This is detailed in Chapter 2. The harmonic voltages can be expressed by:

$$V_h = I_h \cdot Z_h \tag{1.2}$$

where $Z_h = h \cdot Z_1$ is the supply harmonic impedance which has been approximated as purely inductive.

Distortion Factor DF, also known as Total Harmonic Distortion (THD), is a measure of the overall voltage distortion [1] and is defined as:

$$DF = \frac{\sqrt{\sum_{h=2}^{50} V_h^2}}{V_1} \times 100\% \tag{1.3}$$

The IEEE Guide [1] recommends that the voltage distortion factor should not exceed the values listed in Table 1.1. For example, the recommended limit of acceptable voltage distortion on a high-voltage (115-kV or above) power system is 1.5% of the fundamental voltage.

Table 1.1 Voltage Distortion Limits in Power Systems

Power System Voltage Level	Dedicated* Power System	General Power System
Medium Voltage (2.4-69 kV)	8%	5%
High Voltage (115-kV or above)	1.5%	1.5%
* A dedicated system is one servicing only converters or loads not affected by voltage distortion		

Voltage Notch Limits

Three-phase AC/DC converters generate notches on the supply voltage [1]. The detailed mechanism of the notch formation is described in Chapter 4. A temporary short circuit on two supply phases occurs when the AC/DC converter output current is being transferred from one phase to another. This transfer results in a notch on the supply voltages (Figure 1.1). The notch voltage V_N at the point of common coupling in the power system (see Chapter 4) can be expressed by:

$$V_n/V_{\ell-\ell} = L_s/(L_s + L_c) = 1/\rho \tag{1.4}$$

where $V_{\ell-\ell}$ is the line-to-line supply voltage, L_s is supply inductance, L_c is converter input inductance, and ρ is inductance ratio. Similarly, the area of the notch can be determinate by:

$$A_n = V_n \cdot t_n$$

where t_n is the voltage-notch duration. The voltage notch problem is particularly evident in the low-voltage systems. IEEE-519 [1] recommends limits on voltage notches for a 460-V system as given in Table 1.2.

Table 1.2 Voltage Distortion Limits for a 460-V System recommended in the IEEE Guide [1]

Class	ρ	$A_n(V \cdot N_n)$	DF(%)
Special Applications*	10	16400	3
General System	5	22800	5
Dedicated System	2	36500	10
*Special applications are those where the rate of change of voltage notches might mistrigger an event.			

Telephone Interference Limits

Harmonic currents injected by drive converters into the power transmission system may cause interference with communication circuits. A measure of this interference can be expressed as the product of the rms harmonic current I and the Telephone Interference Factor T, which is defined by [1]:

$$T = \frac{\sqrt{\sum_{h=2}^{50} (W_f \cdot X_f)^2}}{X_t} \qquad (1.6)$$

where X_t is the total rms current or voltage, X_f is the single-frequency rms current or voltage, and W_f is the single-frequency interference weighting at frequency f. Table 1.3 shows the I.T product guidelines for the industrial drive converters connected to a power transmission network.

Table 1.3 I.T Product Guidelines for Converter Installations

Category	Descriptions	I.T
Noise sensitive instruments	Levels most unlikely to cause interference	up to 10 kA
Commercial and industrial plants	Levels might cause interference	10 k to 50 kA
Unrestricted areas	Levels probably will cause interference	>50 kA
*I.T products are for communication circuits with an exposure between overhead lines.		

Flicker Limits

Certain converter-drive operations can cause flicker problems. For the machine drives having an input AC/DC converter, the converter itself may not cause a flicker problem. However, the flicker phenomenon may result from special drive operations by applying and removing a motor load at a frequency of 5 to 20 Hz, which is perceptible to the human eye [3]. If the resulting voltage variations are sufficiently large, it can cause a voltage modulation of the lamp light that may be objectionable. Similarly, a large cycloconverter drive which may generate non-characteristic harmonics may also cause a flicker problem.

The severity of flicker is assessed in terms of the level of system voltage variation and the frequency at which the variation occurs. Guidelines on acceptable flicker levels taken from IEEE-519 are given in Figure 1-2.

2. ASSESSMENT OF HARMONICS GENERATED BY VARIABLE SPEED DRIVES

This chapter deals with the quantitative assessment of harmonic disturbances caused by variable speed drives. First, current harmonics generated from one machine drive under both steady-state symmetrical circuit conditions as well as under unsymmetrical operating conditions are assessed. Also, transient disturbances generated by individual drives are studied. Data obtained from this study are particularly useful for assessing harmonic disturbances generated by one large drive connected to a weak power system. Second, these data can provide a basis for estimating the combined harmonic disturbances from several drives. A statistical study of the combined effects of several drives on one local power system is given.

2.1 Steady-State Symmetrical Drive Operations

Figures 2.1 to 2.7 show the configurations of typical variable speed drives. The dc motor in Figure 2.1 is driven by a three-phase AC/DC converter. Figure 2.2 shows a square-wave or pulse width-modulated (PWM) current-source inverter (CSI) drive. The input stage of this drive is a controlled or uncontrolled three-phase AC/DC converter. Similarly, the square-wave or PWM voltage-source-inverter (VSI) drive, shown in Figure 2.3, also has a controlled or uncontrolled AC/DC converter in the input stage. Since all these drives are connected to the power system through a three-phase AC/DC converter, they can be treated as one group for simplifying the analysis of their input harmonics.

With the assumption that the converter output is a constant dc current and the source impedance is negligible, the theoretical current harmonics on the supply side [1,4,5] have the order of:

$$h = kq \pm 1 \tag{2.1}$$

where h = order of harmonics, k = integer: 1, 2,..., and q = number of pulses. The amplitudes of these harmonics are:

$$I_h = I_1/h \tag{2.2}$$

where I_1 = amplitude of fundamental current, and I_h = amplitude of harmonic current. However, as a finite source impedance reduces the rate of change of input currents, the actual harmonic amplitude will be less than that predicted in Eq. (2.2). Typical values of input current harmonics including effects of commutating reactors are given in Table 2.1 for drives shown in Figures 2.1, 2.2, and 2.3 [5].

Table 2.1 Typical Input Harmonics

Harmonics	1st	5th	7th	11th	13th
Amplitudes	1	.175	.110	.045	.029

Another group of motor drives is given in Figures 2.4 - 2.6 which are three typical direct AC/AC converter drives. Figure 2.4 shows a phase-controlled induction motor drive. Its current harmonics on the supply side vary with the motor speed. These are shown in Figure 2.8 [5]. This type of drive, however, has a limited application. Figure 2.5 shows a cycloconverter used to drive an induction motor on the stator side. Similarly, Figure 2.6 shows a cycloconverter (Scherbius) drive on the rotor side. The frequency of input harmonics depends on the motor speed [5]:

$$f_h = f_1(6k \pm 1) \pm 6nf_o \quad (2.3)$$

where f_h = harmonic frequency, k = integer: 1, 2,..., n = integer: 0, 1,..., f_1 = line fundamental frequency, and f_o = output frequency. Finally, a slip-energy recovery (Kramer) drive is shown in Figure 2.7. The input-harmonic frequency of this drive [5] is given by:

$$f_h = f_1(kq \pm 1) \pm f_r\,(6k \pm 1) \quad (2.4)$$

where f_r = rotor frequency, and q = number of pulses.

In general, the above equations can be used to estimate the characteristic harmonics generated by commonly used drives under the steady-state symmetrical operations. However, an accurate prediction of drive harmonics requires computer simulations.

2.2 Steady-State Unsymmetrical Drive Operations

This section estimates harmonics generated by converter drives under typical unsymmetrical operating conditions, such as deviations in thyristor firing-angles, unbalanced voltages and unbalanced input impedances. Under these unsymmetrical operations, the converter drives will generate non-characteristic harmonics in addition to the characteristic harmonics predicted in the previous Section 2.2. For example, a variable speed drive having a controlled AC/DC converter (Figures 2.1 -2.3) will generate characteristic harmonics under a symmetrical operating condition. The harmonic spectrum of the line currents is shown in Figure 2.9(a). If the firing angles for this converter become unsymmetrical, some non-characteristic harmonics will appear as shown in Figure 2.9(b) [6,7].

The analysis of non-characteristic harmonics for a detailed drive system usually requires computer simulations. A drive system given in Figure 2.10(a) was simulated [7]. This drive system has two synchronously controlled six-pulse converters fed by two Y/Y and Δ/Y-connected transformers. Under a symmetrical operating condition, the drive characteristic harmonics for a twelve-pulse drive system have the order of $12h \pm 1$ which can be predicted from Eq. (2.1). The 5th and 7th harmonics are eliminated. The harmonic spectrum is shown in Figure 2.10(b).

An unsymmetrical operation was simulated in [7] and its result is given in Figure 2.10(b). This simulation assumed a deviation of one electrical degree in the firing angles for the two six-pulse converters. This simulation showed that the input currents exhibit some uncharacteristic even harmonics (about 1% for the 4th, 6th and 12th harmonics). A dc component is also present on the line current (1.5% of the HV transformer currents). Furthermore, the 5th and 7th harmonics are not completely eliminated in the line current.

Another unsymmetrical circuit condition was simulated for the drive system shown in Figure 2.10(a). A discrepancy of 1% between the transformer-leakage reactances was assumed. The harmonic spectrum for the line current is given in Figure 2.10(b). The 5th and 7th harmonics appear at levels of about 1%. A further discussion of harmonic disturbances caused by unsymmetrical circuit conditions is given in Chapter 3.

2.3 Transient Drive Operations

This section shows three examples of harmonic disturbances caused by variable speed drives during transient operations.

The first example illustrates the switching transients of a dc motor drive or a PWM VSI ac motor drive (Figures 2.1 and 2.3). In this example, the drive AC/DC converter connected to the power supply network is operated at a constant firing angle and a constant dc voltage. A simplified circuit for the analysis is shown in Figure 2.11. During the energizing period, the load current increases exponentially [8]. The input current contains not only the characteristic harmonics (h = 5, 7,...) but also non-characteristic harmonics (h = 2, 3, 4, 6,...). Figure 2.11 shows the variation of harmonics during a rise in the load current. When the steady-state condition is reached, only the characteristic harmonics remain. The computed results shown in Figure 2.12(a) will be used to compare this disturbance with the disturbances discussed in the following two examples.

The second example shown in Figure 2.12(b) demonstrates the transient disturbances generated by a square-wave or PWM current-source-inverter (CSI) ac motor drive when the inverter input voltage increases linearly [8]. The variation of input harmonics is quite similar to that of the first example. The non-characteristic harmonics occur during the transient, but they disappear when the steady-state condition is achieved.

The third example given in Figure 2.12(c) shows the results when both the firing angle and the converter-output current are varied simultaneously as is the case for the cycloconverter drive. The input current harmonics [5] have frequencies of:

$$f_h = f_1(6h \pm 1) \pm 2nf_0 \qquad (2.5)$$

where f_0 = output frequency, f_1 = line frequency, h = integer: 1, 2,..., and n = integer: 0, 1,... Further studies of the transient disturbances which may affect the machine drive performance are given in Chapter 3.

2.4 Harmonic Disturbance from Multiple Drives

This section assesses the combined harmonic disturbances caused by several variable speed drives on the same power system [9,10]. If the n^{th} harmonic of a drive "i" is expressed by a phasor a_i, then the combined n^{th} order harmonic for a multiple drive system will be:

$$S_i = \sum a_i \qquad (2.6)$$

This combined harmonic will be generally less than the arithmetic sum of individual harmonic amplitudes due to the non-coincident phase angles (Figure 2.13) [9]. Two typical examples are given below.

2.4.1 Fixed Amplitudes and Random Phases

The first example assumes all harmonic phasors having a fixed amplitude A_i but random phase angles θ_i. Also, the harmonic phase angles are assumed to have an uniform-density function of [9]:

$$f_\theta(\theta_i) = 1/2\pi \qquad 0 < \theta_i < 2\pi \qquad (2.7)$$

If the number of drives N is sufficiently large, the expected value of the combined harmonic is given by:

$$E(S) = \sqrt{(\pi/2)} \cdot Rss \tag{2.8}$$

where Rss is the root sum square of the amplitudes of all individual phasors:

$$Rss = \sqrt{\sum_{i=1}^{N} A_i^2}$$

Also, the probability of a combination of harmonics that would exceed the Rss value is given by [9]:

$$P\{S > Rss\} = 0.368 \tag{2.9}$$

A computer program was written [9] to simulate the summation of random phasors. Figure 2.14 compares the mean expected voltages of N harmonic phasors calculated from the formulae given above with those obtained from the computer simulation.

2.4.2 Random amplitudes and Random Phases

The second example assumes that the harmonic phasors have random phase angles and random amplitudes. Both phase and amplitude have uniform distribution functions:

$$f_0(\theta_i) = 1/2\pi \qquad 0 < \theta_i < 2\pi$$
$$f_a(a_i) = 1/A_i \qquad 0 < a_i < A_i \tag{2.10}$$

Then, the expected value of the combined harmonic [9] is given by:

$$E(S) = 1/2\sqrt{(\pi/3)} \cdot Rss \tag{2.11}$$

Also, the probability of the combined harmonic value that would exceed the Rss value is:

$$P\{S > Rss\} = 0.0498 \tag{2.12}$$

Figure 2.15 shows the computed values and simulated results of the mean expected value of N harmonic phasors. These two examples show that the combined harmonics generated by multiple drives are generally less than the arithmetic sum of all harmonics given by the individual drives, owing to the inconsistency of their harmonic amplitudes and phase angles. For a better estimation, an accurate prediction of the distribution functions of drive harmonic amplitudes and phases is required. These could be obtained by field measurements.

3. IMPACTS OF SYSTEM DISTURBANCES ON VARIABLES SPEED DRIVES

This chapter examines the impacts of power system disturbances on variable speed drive performance. Recently, with increasing use of static converter drives, there has been a growing concern about the effects of power quality on the performance of these drives. However, very few studies about the susceptibility of variable speed drives to harmonic disturbances have been reported in the literature. This chapter presents several examples of typical power system disturbances that could cause these drives to fail.

3.1 Drive Configurations and Disturbances

This section describes certain types of drive configurations that may be vulnerable to particular power-system disturbances.

The most widely used variable speed drives are AC/DC converter dc drives, AC/DC/DC converter-chopper dc drives and AC/DC/AC converter-inverter (Square-Wave, PWM, VSI, CSI) ac drives as shown in Figures 2.1 - 2.3. All these drives have an AC/DC converter at the input circuit connected to the supply system and a dc link at the converter output. This dc link consists of a large inductor and/or a big capacitor which can provide a buffer for the electric machine from the power system disturbances. Therefore, the major impact of power-system disturbances would be on the input AC/DC converter and not the motor drive.

In an AC/DC converter, the control or firing signals for the switching devices (SCR, GTO, etc.) must be synchronized with the power system voltages with respective to their zero-crossings. A disturbance in the supply-system voltage may cause the converter to be misfired, or it may fail the converter commutation. This could result in dangerous overcurrent, particularly when the drive converter is operating in a regenerative braking mode, converting the dc power back into ac. Fortunately, the drive converter normally operates in a rectifying driving mode. Also, most of harmonic disturbances in the power system may not be severe enough to cause a converter commutation failure.

AC/AC converter drives or cycloconverter drives are more vulnerable to the power system disturbances, since these drives are directly connected to the power system (without a dc-link buffer, for example). Also, the drive output is synthesized directly from the three-phase supply voltage. Any significant disturbance would considerably alter the converter-control signals and therefore would affect the drive performance.

3.2 Severe Supply Voltage Dip

If a severe supply-voltage dip occurs in the power system during a rectifying operation of the AC/DC drive converter, this may result in a proportional drop in the output dc voltage. The output dc current therefore becomes smaller. This normally would not affect the drive performance significantly. However, if the drive converter is in the inverting operation, the consequence could be serious. For example, a temporary large reduction in the supply voltage would cause an increased current at the converter output. This can cause a failure in the thyristor commutation, resulting in a loss of converter control. The failure mechanism is described below.

The commutation angle μ is a function of the firing angle α, output current i_d and supply voltage v_s [11]:

$$\mu = f(\alpha, i_d, V_s) \tag{3.1}$$

In an inverting operation, the commutation angle increases with the increasing firing angle and output current. Similarly, the angle also increases with a decreasing supply voltage. For a severe supply-voltage dip, the commutation angle becomes progressively larger and the load current increases, if the dc voltage and the firing angle remain unchanged. Then, the increasing commutation angle would lead to a commutation failure.

Figure 3.1 illustrates a process of the commutation failure due to a supply-voltage dip [12]. This figure shows that at a critical instant Thyristor 2 is being triggered, even though the commutation between Thyristors 1 and 5 has not been completed due to an increased commutation angle caused by the supply-voltage dip. Therefore, the output current has not been transferred completely to Thyristor 1 from Thyristor 5. The turning-on of Thyristor 2 by the normal firing sequence would cause a short circuit (a by-pass path) on the dc side. Thyristors 2 and 5 will then be permanently conducting. Therefore, the commutation process for Thyristor 5 fails and the converter is no longer controllable, resulting in a dangerously heavy current on the dc side.

Similarly, a severe voltage dip can also lead to a different mode of commutation failure as illustrated in Figure 3.2 [11]. This figure shows a short-circuit path resulting from a commutation failure. This short circuit passes through the two commutating inductors, ac voltage source, load inductor and dc source representing the motor's back emf. In this case, the direct current may be modulated by ac supply voltages, and Thyristors 4 and 5 will be conducting continuously. This would result in a dangerous overcurrent flowing in the converter.

3.3 Supply Voltage Unbalance

This section shows two cases of supply-voltage unbalances that would affect the drive-converter performance. The first case is when one of the three supply phases is lost. The converter may be operating in a limited two-pulse operation mode. The gating signals in the thyristor control system are not exactly the same as those required for a single-phase two-pulse operation. The converter, therefore, cannot operate at its maximum output power in a two-pulse operating mode. Also, under certain conditions, it may exhibit a freewheeling operation [12]. Figure 3.3 shows the load characteristics for a firing angle $\alpha = 0$ in such an output-limited two-pulse mode, as compared to a three-phase converter operation. This figure also shows that the maximum output of the drive converter is reduced. As a result, for a dc drive or a voltage-source-inverter (VSI) ac drive, the range of speed control will be reduced. Similarly, for a current-source-inverter (CSI) ac drive, the torque control range will also be limited.

Another example of supply unbalances that would affect the drive performance is when a fault occurs across two of three input phases [11]. Figure 3.4(a) gives a drive-input circuit, and Figure 3.4(b) shows the unbalanced voltage waveforms in the primary and secondary windings of input transformers during a fault period. The voltage unbalance may reduce the voltage amplitude of the commutating phase. This would increase the commutation angle μ. If this angle becomes greater than π radians, then the commutation process will fail.

In addition, the non-sinusoidal input shown in Figure 3.4 (b) would cause a displacement of voltage-zero crossings. Then, the control synchronization may be jeopardised. This can also contribute to a false commutation by misfiring the thyristors. When a false commutation or a misfiring occurs, the dc current will increase abnormally and the commutation angle will increase. In a rectifying operation, the consequence is simply a reduction of the output power and temporary firing control difficulties. In an inverting operation the converter may lose control, because of eventual short circuits caused by the non-commutated thyristors. Figure 3.4(d) shows an example of such a commutation failure [11].

3.4 Harmonic Disturbances in Supply System

Small harmonic disturbances generated by neighbouring drive systems may jeopardise the normal operation of variable speed drives. However, they would not usually fail the drive system. The disturbances may jeopardize the drive-synchronization control resulting in an increased generation of harmonics. The characteristic input harmonics would be increased, and other non-characteristic harmonics would also appear. Two cases were simulated [7] using the drive given in Figure 3.5(a). The first case assumed a voltage distortion by adding 3% of 5th harmonic and 1% of 7th harmonic on the supply fundamental. This simulated a small disturbance from a neighbouring drive. The computed result is shown in Figure 3.5(b). The second case assumed a voltage unbalance by superimposing 1% of negative sequence voltage to the rated positive sequence value. The result is given in Figure 3.5(b). Of particular significance from these simulated results is that the third harmonic and its odd multiples are predominant among all non-characteristic harmonics.

4. CONTROL OF HARMONICS FROM DRIVES

This chapter proposes solutions for controlling harmonic disturbances from the variable speed drives. In general, a converter drive can be treated as a harmonic-current generator. The magnitudes of drive-current harmonics are assessed in Chapter 2. This chapter describes several possible measures for suppressing these harmonics. These measures include the multiphasing of drive converters, application of pulse-width-modulation (PWM) techniques and installation of passive and active filters.

4.1 Voltage Harmonics and Notches from Drives

This section describes some possible measures to reduce the supply-voltage harmonics and notches generated by drive converters [13,14]. For a simple analysis of these harmonic-control methods, the drive converter will be treated as a harmonic-current source. Figure 4.1 shows an equivalent circuit. The current harmonics I_h generated by a drive converter will flow through the supply impedance, resulting in voltage harmonics V_h at the point of common coupling (PCC):

$$V_h = h\omega L_s \cdot I_h \tag{4.1}$$

where L_s is the equivalent supply inductance. These harmonic voltages can be normalized with respect to the supply fundamental voltage v_1 as follows [2]:

$$V_{hpu} = V_h/V_1 = h\omega L_s \cdot I_h/V_1 = h \cdot I_h/I_{sc} \tag{4.2}$$

where I_{sc} is the short-circuit current at PCC. This equation shows that harmonic voltages can be reduced by either reducing the harmonic currents injecting into the power system or increasing the short-circuit level at PCC.

Another power-quality problem caused by drives having an AC/DC converter is the generation of notches on the supply voltage. Figure 4.2 illustrates the mechanism of the notch formation. When the converter output current is being transferred from one phase to another during a commutation, the two supply phases are short-circuited temporarily by the converter. During this commutation period, a notch is therefore created on the supply voltage. The magnitude or depth of the voltage notch can be estimated from the simplified equivalent circuit shown in Figure 4.2:

$$V_n/V_s = L_s/(L_s + L_c) \tag{4.3}$$

where L_c is the equivalent inductance at the converter input, and V_s is the instantaneous line-to-line supply voltage. Similarly, the notch duration t_n and notch area A_n can be estimated as follows:

$$t_n = 2(L_s + L_c) \cdot I_d/V_s \tag{4.4}$$

and,

$$A_n = V_s \cdot t_n = 2L_s \cdot I_d \tag{4.5}$$

These equations show that a reduction of the supply inductance L_s would minimize the magnitude, duration and area of supply-voltage notches during a thyristor commutation. Also, a reduction of the converter inductance L_c would decrease the notch duration but increase its magnitude. This is obvious since the decrease of inductances accelerates the current commutation process or reduces the notch duration. Table 4.1 shows several possible measures for reducing voltage disturbances from drives that are discussed in the following sections.

Table 4.1 Possible Solutions for Harmonic Control

Technique	Measures
A) Reduce "Harmonic Currents" injected from drive converters	1. Increase converter pulses (multiphasing) 2. Apply force-commutated PWM techniques 3. Install passive power filters 4. Install active power filters 5. Use uninterruptible power supply
B) Reduce "L_s" to minimize Harmonic Voltage, Notch Depth and Area	1. Connect to a higher voltage system 2. Install a separate distribution transformer 3. Install parallel feeders 4. Connect to a larger distribution transformer
C) Reduce "L_c" to minimize Notch Magnitude	1. Install an isolation transformer 2. Install an input reactor

4.2 Multiphasing of Drive Converters

This section describes how harmonic disturbances from variable speed drives can be reduced significantly by multiphasing the drive-input converters [1,4]. As discussed in Chapter 3, the characteristic input harmonics of AC/DC drives, AC/DC/DC drives and AC/DC/AC drives have the harmonic order of:

$$h = kq \pm 1 \tag{4.6}$$

where q is the pulse number of the AC/DC converter. Also, the amplitudes of input-current harmonics for a constant dc current can be estimated by:

$$I_h = I_1/h \tag{4.7}$$

These equations show that an increase of the pulse number q can eliminate a major portion of input harmonic currents. The total harmonic distortion can, therefore, be reduced significantly. For example, if a six-pulse AC/DC converter is replaced by a twelve-pulse converter, a large portion of harmonics (5th, 7th, 17th, 19th,...) will be eliminated. For the cases of unsymmetrical or unbalanced operations, even if these harmonics may still exist, their amplitudes would be much smaller than those appearing in the original six-pulse converter. Figure 4.3 shows a system of multiphasing two six-pulse converters to obtain a twelve-pulse converter. In this system, one six-pulse converter is supplied through a Y/Y-connected transformer, and the other converter is supplied through a Δ/Y-connected transformer to obtain a required phase shift of 30°. These two converters are connected and controlled in parallel to achieve a twelve-pulse operation. The input currents for each of these two converters (shown in

Figure 4.3) have harmonics of the same amplitudes, but the 5th, 7th, and 17th, 19th,... harmonic currents are out-of-phase, and therefore they cancel each other. The combined input current becomes closer to sinusoidal, and its lowest order of harmonics starts at 11.

4.3 Pulse-Width-Modulation (PWM) Control

Recently, in order to reduce the reactive power requirements for the AC/DC converter and to minimize the harmonic components in the input line current, the forced-commutated pulse-width-modulation (PWM) techniques have been used for AC/DC converter control. This applies to both dc and ac variable speed drives with input AC/DC converter. The following describes the characteristics of these converters: PWM voltage-output converter and PWM current-output converter [15,16,17].

4.3.1 PWM Voltage-Output Converter

A typical configuration of PWM AC/DC voltage-output converters for dc and ac drives [15] is shown in Figure 4.4(a). The three-phase inductor L at the input is employed to block the current harmonics generated by the converter. Similarly, the capacitor C on the dc side is used to minimize the voltage harmonics at the converter output. The load can be a dc machine, a chopper driving a dc machine, or a voltage-source inverter driving an ac machine. Figure 4.4(b) shows a single-phase representation of the converter. The voltage V_p can be regarded as being modulated from the dc voltage and consists of a fundamental component V_{p1} together with harmonic components V_{ph}. Figure 4.4(c) shows the two equivalent circuits representing these voltage components. The fundamental current I_1 can therefore be determined:

$$I_1 = (E - V_{P1})/j\omega L \tag{4.8}$$

where E is the supply voltage. Similarly, the input harmonic current I_h is given by:

$$I_h = V_{ph}/jh\omega L \tag{4.9}$$

The phase and amplitude of the fundamental voltage V_{P1} can be controlled by adjusting two variables: ψ (phase) and M (magnitude). Figure 4.5 shows the phasor diagrams of the fundamental component under typical operating conditions. By adjusting ψ and M to alter the phase and amplitude of V_{P1}, both the line current I_1 and the input-power-factor angle ϕ_1 can be controlled. The angle ϕ_1 can be located anywhere in all four quadrants of operations. Nevertheless, the phase and amplitude of V_{P1} are usually regulated to achieve either a unity power factor or, in certain applications, a leading power factor for providing reactive power to the supply system.

If the converter is controlled using a sinusoidal-pulse-width-modulation (SPWM) technique, only fairly high-frequency harmonics (mainly of the switching frequency) would exist in V_{ph}. The switching frequency is usually in the range of several thousand Hertz. At such a high frequency, the input inductor can effectively reduce the harmonic current I_h. Figure 4.6 gives the waveforms of the line current and line-to-neutral voltage at the converter input. This figure shows that the input current is approximately sinusoidal and almost in-phase with the phase voltage giving a close-to-unity power factor.

4.3.2 PWM Current-Output Converter

Figure 4.7 shows a typical circuit configuration for PWM current-output converters for ac drives [16,17]. This AC/DC current-output converter is a dual version of the voltage-source converter (Figure 4.4). The inductor at the output acts as a dc current filter. Similarly, the input capacitor is used to absorb voltage transients produced by converter switches when they are turned off. Also, these capacitors can act as a filter for the converter input current. This current has a chopped waveform as shown in Figure 4.8, when the converter is controlled using SPWM

techniques. Most high-frequency harmonics in the chopper currents are absorbed by the input capacitor. Therefore, the input current from the supply will be nearly sinusoidal as shown in Figure 4.9.

4.4 Passive Power Filters

Power filters for suppressing current harmonics from drive converters usually consist of simple combinations of resistors, inductors and capacitors "RLC" [18-20]. Two types of commonly used power filters are series filters and shunt filters as shown in Figure 4.10. A series filter is simply a low-pass filter, having a three-phase inductor in series between the supply and drive converter and a parallel three-phase capacitor connected to ground. Ideally, this filter passes the fundamental current virtually unattenuated while it bypasses high-frequency currents to ground. This filter, therefore, can effectively suppress the current harmonics from variable speed drives. However, a major drawback of this filter is that it must be rated to the full-load current, since the filter inductor is placed in series with the converter load. Thus, this filter could be quite expensive.

On the other hand, the shunt filters shown in Figure 4.10(b) will carry only a fraction of the rated load current. These shunt filters may also supply the reactive power at the fundamental frequency to the drive system for improving its input power factor. Therefore, shunt filters become practical filter configurations for drive systems. The most common configurations of shunt filters are single-tuned and high-pass, shown in Figure 4.10(b). They are simple and less expensive to implement. For effectively reducing drive-harmonic currents flowing into the ac power system, several single-tuned filters and one high-pass filter are usually connected at the input of the drive system. Each single-tuned filter is adjusted to attenuate a specific harmonic, for example starting from the 5th, 7th, 13th harmonics for a six-pulse AC/DC converter. A high-pass filter is used to attenuate the rest of the harmonics, which include the 17th harmonic and higher.

A shunt filter, if not properly designed, can be resonant in parallel with the power system impedance at a particular frequency of converter-input harmonics. The parallel resonant frequency would be:

$$f_{sys} = 1/2\pi \sqrt{(L_s + L)C} \qquad (4.10)$$

where L_s is the system inductance. This combined resonant frequency is, therefore, lower than the series resonant frequency of the filter itself. Figure 4.11 shows the combined impedance for the filter and supply system, which varies with frequency. If a current harmonic injected from a drive converter has a frequency close to this combined resonant frequency f_{sys}, the resulting harmonic will be amplified. Therefore for a group of single-tuned filters, the lowest combined parallel-resonance frequency should be designed to be smaller than the lowest order of current harmonics injected from the drive converter.

4.5 Active Power Filters

Passive RLC power filters have been commonly used for absorbing harmonic currents generated by drive converters. However, these filters may have several drawbacks. For example, the filter-resonance frequencies are fixed. The filter, therefore, cannot effectively absorb the varying-frequency harmonics created by certain converters, such as the cycloconverter where the harmonic frequency changes with the load frequency. In addition, a parallel resonance between the passive power filters and system impedance can cause excessive amplification of certain harmonic currents.

Recently, active power filters using force-commutated inverters have been introduced for drive applications. This type of filter can absorb harmonic currents with time-varying frequencies, since its output can be controlled according to the variation of harmonic currents [21-25]. In addition, an active filter can provide some damping to the parallel resonance circuit. It can also suppress the harmonic-current amplification due to a parallel resonance.

Figure 4.12 shows a block diagram of the active power filter. A pulse-width-modulated (PWM) voltage-source converter is used as a harmonic compensator which is controlled in a closed loop to actively shape the supply system current "i_s" into sinusoidal. In other words, it injects a compensating current i_c into the supply system to cancel the harmonics contained in the drive current "i_L". Figure 4.13 shows the configuration of an active power filter. The calculation circuit for the harmonic-current control consists of the following three parts:

The first part is the computation of the real and imaginary powers, "p_L" and "q_L". This computation initially converts the three-phase supply voltage and load current into dq quantities:

$$\begin{bmatrix} e_{dq} \end{bmatrix} = \begin{bmatrix} T \end{bmatrix} \cdot \begin{bmatrix} e_{abc} \end{bmatrix}$$
$$\begin{bmatrix} i_{Ldq} \end{bmatrix} = \begin{bmatrix} T \end{bmatrix} \cdot \begin{bmatrix} i_{Labc} \end{bmatrix} \qquad (4.12)$$

where

$$[T] = 2/3 \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & 3/2 & 3/2 \end{bmatrix}$$

Then, the instantaneous powers will be calculated according to:

$$\begin{bmatrix} P_L \\ q_L \end{bmatrix} = \begin{bmatrix} e_d & e_q \\ -e_q & e_d \end{bmatrix} \cdot \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} \qquad (4.13)$$

The real and imaginary powers will contain both dc and ac components. The dc component represents the fundamental load current, and the ac component corresponds to the harmonic currents. In the second part of this calculation circuit, a high-pass filter is used to obtain the ac components of the instantaneous power:

$$\begin{bmatrix} P_h \\ q_h \end{bmatrix} = G \cdot \begin{bmatrix} P_L \\ q_L \end{bmatrix} \qquad (4.14)$$

where G is the transfer function of a high-pass filter. The third part of the calculation circuit in Figure 4.13 shows that the ac power components are used to obtain the compensating current commands as follows:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = [T]^t \cdot \begin{bmatrix} e_d & e_q \\ -e_q & e_d \end{bmatrix} \cdot \begin{bmatrix} p_h \\ q_h \end{bmatrix} \qquad (4.15)$$

These current commands will be sent to control the PWM voltage-source converter which operates as a current controller and generates the three-phase compensating currents i_{ca}, i_{cb}, i_{cc}. These currents are then injected into the supply system to make the shape of the input current more sinusoidal. Figure 4.14 shows the experimental waveforms of the load current i_{La} and the input line current i_{sa}.

This active power filter seems very effective for reducing harmonics of varying frequencies. However, it is difficult, to date, to realize a large VA-rating PWM converter which can have a fast response and low loss. A combination of active and passive filters would produce an effective harmonic-suppression system. For a harmonic-varying system, an active filter can be used to absorb lower-order harmonics and a passive filter to eliminate the higher ones. Based on such a combination, one harmonic-current compensation system has been installed for absorbing harmonic currents generated by cycloconverters [21].

5. POWER QUALITY CONTROL RESEARCH

Several interesting research projects focusing on the power-quality control for variable speed drives are proposed. These include the development of a general computational package for power quality assessment, design and analysis of passive and active power filters for controlling drive harmonics, and analysis of effects of new drive configurations on power quality. This chapter describes the needs, objectives and scopes of these projects:

i) Computational package for power quality analysis of variable speed drives.

ii) Analysis of effects of new drive configurations and their controls on power quality, particularly for drive converters with PWM controls.

iii) Development of a general design strategy or computer algorithm for the optimal passive power filter which can meet a specified power-quality requirement.

iv) Feasibility study of active power filters for power-quality improvement. This project can be extended to obtain the necessary design data.

v) Analysis of the performance of typical drive systems under non-ideal operating conditions. In particular, the analysis should focus on the impacts of non-ideal operations on power quality.

vi) Study of combined power-quality effects of several drives connected on the same power distribution system. This study also assesses the susceptibility of individual drive performance in the presence of other harmonic sources in a local distribution system.

vii) Power quality study of a local power system having several variable speed drives and reactive-power compensation systems. In particular, the study should assess the possibility of a parallel resonance condition.

5.1 Power Quality Computational Package

This section proposes a research project on the development of a computational package for the power-quality analysis of variable speed drives. The need, objective and scope of this package are described as follows:

Harmonics injected from variable speed drives into a power system must be assessed and controlled effectively to maintain the system with good power quality. Several computer programs like *Cymharmo*, *Vharm* and *Qharm* can be employed to assess the harmonic impacts from machine drives on the utility system. These programs, however, assume a very simple model for all drive harmonics. Hence, harmonics generated by various machine drives cannot be accurately predicted, particularly for drives using sophisticated PWM controls. These programs also cannot predict the effects of non-characteristic drive harmonics or transients on a power system. Consequently, these programs can only give a fairly general prediction of effects of drive characteristic harmonics on a large power system. Therefore, there is a need for a general computer program to compute all drive characteristic and non-characteristic harmonics accurately.

The objective of this project is to develop a general computational package for power-quality analysis. This package will focus on the computation of drive harmonics, and their impacts on power quality of the supply system. As well, the effects of power-system disturbances on the drive performance will be considered.

This package will include several features. First, it will simulate the performance of various drives. Second, it will assess the power-quality effects of drive-control dynamics. Third, it will compute accurately the harmonics generated from various drives. The package will have a power-circuit module to model the drive circuit and the supply system accurately. It will also have a control-circuit module to model a detailed drive control, particularly one using a sophisticated PWM strategy. Furthermore, the package will be able to compute the filter requirements to meet a power-quality specification.

5.2 Analysis of New Drive Configurations and Controls

The second research proposal is to analyze several new drive configurations and their controls, and also to assess their effects on the power quality of supply systems. This proposal is described below:

Recently, several new PWM control strategies have been employed for controlling variable speed drives having an input AC/DC converter. These controls are designed to reduce the filter requirements at the input as well as the output of the AC/DC converter. They are also intended to increase the drive-input power factor. However, these new drive configurations and controls may be more vulnerable to certain power-system disturbances. They may generate additional harmonics under a power-system disturbance, or they may amplify the existing harmonics. Hence, it is necessary to predict accurately the effects of these new drive controls on power quality and also on the drive itself, if there is a disturbance in the power system. Therefore, the objective of this project is to analyze the effects of several new drive configurations and their controls on the power quality of supply systems, under normal operating conditions and under certain power-system disturbances.

5.3 Optimal Design of Passive Power Filters

The third research proposal is to develop a computer program for the optimal design of passive power filters used in variable speed drives, as described in the following:

The amount of harmonics injected by variable speed drives must be controlled effectively in order to maintain acceptable power quality in the supply system. A proper design of passive RLC power filters can meet a specified power-quality requirement. These power filters are usually designed based on some simplified drive models including certain conservative design factors. Also, they are often installed immediately at the input of an individual drive system. Consequently, these filters may not be properly designed or would not be optimized, particularly when a power-quality requirement is not located right at the drive input terminal. Hence, there is a need for a computer program which can automatically search the optimal power-filter design to satisfy a specified power-quality requirement. Therefore, the objective of this project is to develop software for the design optimization of a passive power filter to reduce harmonics generated from variable speed drives and to improve the drive-input power factor.

5.4 Analysis and Design of Active Power Filters

The fourth research proposal is to analyze and design an active power filter for variable speed drives. This project is described in the following:

> Variable speed drives using a direct AC/AC conversion technique can generate various harmonics. These harmonics will be dependent on the modes of drive operations. Usually, the passive power filters could not effectively suppress these harmonics having varying amplitudes depending on the drive operations. Recently, active power filters have been reported to provide a very attractive solution. These filters can ideally track the changes of drive harmonics and suppress the major harmonics in any mode of drive operations. However, this filter control technique is fairly new and its practical aspects have not been fully understood in the industry. Hence, it is necessary to fully analyze the practical aspects of active power filters and to obtain the design data. This project should analyze and design an active power filter for variable speed drives, particularly for drives using direct AC/AC converters. The impact of the active filter should be evaluated under a normal operating condition as well as under a transient condition.

5.5 Analysis of Drive Systems under Non-Ideal Operating Conditions

The fifth research proposal is to analyze the effects of variable speed drives under non-ideal operating conditions on power quality of the supply system. This proposal is described in the following:

> To date, very few studies have been reported on the effects of variable speed drives on power quality under non-ideal operating conditions. Though several qualitative descriptions of non-characteristic harmonics produced by non-ideal drive operations can be found in some texts, the quantitative studies are sparse. It is important to predict the accurate effects of certain non-ideal drive operations on power quality, particularly when other harmonic sources are also present on the same local power system. Therefore, the objective of this project is to analyze the effects of variable speed drives under non-ideal operating conditions on power quality of the supply system. Also, comparisons to the ideal operations should be made.

5.6 Analysis of Local Power Systems with Multiple Drives and Other Harmonic Sources

The sixth research proposal is to analyze the combined effects of several drives on power quality of a local supply system in the presence of other harmonic sources, as described below:

> Recently, more concern has been on the effects of power quality when several drives are connected on a weak local power system. However, very few studies have addressed this scenario. It is generally predicted that the combined harmonics would be less than the arithmetic sum of harmonics from each individual drive. Actual quantitative data of these combined effects is not available. Therefore, the objective of this project is to analyze the combined effects of several drives on the power quality of a local system, in the presence of other harmonic sources such as arc furnace system.

5.7 Analysis of Reactive Power Compensation and Drive Systems

The last research proposal is to analyze the impacts of a variable speed drive and a parallel-connected reactive-power compensation system on power quality, as described in the following:

> A parallel resonance condition can be excited by drive harmonics when a reactive-power compensation system is connected in parallel with filters associated with a drive. Such a resonance may result in large oscillating currents and consequently high harmonic voltages. These high voltages and large currents can cause equipment insulation failure, capacitor fuse melting, and excessive protective equipment operations. Hence, it is important to identify if any drive operating condition could be vulnerable to a resonance when there exists such a parallel circuit. Therefore, the objective of this project is to analyze the combined effects of a variable speed drive and a parallel-connected reactive-power compensation system on the power quality of the supply system.

6. CONCLUSIONS

This project has provided a brief qualitative and quantitative study of power quality aspects of variable speed drives. In particular, this project has investigated the general impacts of characteristic and non-characteristic harmonics from typical drives on power quality. Also, it has assessed the susceptibility of variable speed drives under certain power-system disturbances. As well, this project has proposed seven research topics on the power-quality control. A summary of the investigations is given below.

1. *Drive disturbance limits*: The limits of converter-drive disturbances on voltage distortion, voltage notch, telephone interference, and flicker were studied. The tolerable voltage-distortion factors on different power systems were listed. Also, limits of voltage notch caused by converter commutation were given.

2. *Characteristic drive harmonics*: The characteristic harmonics generated by standard drive converters under the steady-state symmetrical operations were predicted. In general, a fixed pattern of harmonics will be injected from standard drives having an input AC/DC converter into the power system. However, the harmonic pattern generated by drives with direct AC/AC converters will change according to the operating conditions.

3. *Non-characteristic drive harmonics*: The non-characteristic harmonics generated by drive converters under typical unsymmetrical operating conditions were investigated. Whenever the firing control is jeopardized due the circuit unbalance, certain non-characteristic harmonics will be generated in addition to the predicted ones.

4. *Harmonics from multiple drives*: The combined harmonic disturbances caused by several variable speed drives on the same power system were studied. The computed results showed that the combined harmonics are generally less than the arithmetic sum of all harmonics generated by the individual drives, due to the non-coincident phase angles.

5. *System-disturbance susceptibility of drives*: The impacts of power-system disturbances on variable speed drive performance were assessed. A severe supply voltage dip can fail the drive-converter commutation. Also, the supply power system unbalance can jeopardize the converter performance. On the other hand, small harmonic disturbances, for example from a neighbouring drive system, will not usually fail the drive converter.

6. *Control of drive harmonics*: Several methods for the control of drive harmonics were studied. Particularly, the drive harmonics can be effectively reduced by multiphasing of drive converters, using efficient pulse-width-modulation controls, or installing power filters.

7. *Passive and active power filters*: Several power filter configurations were investigated. The passive RLC power filters have been commonly used for absorbing harmonics from drive converters. However, these filters cannot effectively absorb the harmonics of varying frequencies created by certain converters such as cycloconverter. A recent development of active power filters using force-commutated inverters seems capable of absorbing harmonic currents with time-varying frequencies.

8. *Power quality research proposals*: Seven research projects have been proposed. These include the development of a general computational package for power quality assessment, design and analysis of passive and active power filters for controlling drive harmonics, and analysis of effects of new drive performance on power quality.

REFERENCES

[1] "IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters," ANSI/IEEE Std 519, 1981.

[2] C.K. Duffey and R.P. Stratford, "Update of Harmonic Standard IEEE-519 Recommended Practices and Requirements for Harmonic Control in Electric Power Systems," IEEE/IAS Annual Conf. Record, 1989, pp. 1618 - 1624.

[3] K.G. Williams and G.A. Hanley, "Sources and Control of Mains Distortion Voltage," IEE International Conf. on Industrial Power Engineering, 1986 (Conf. Publ 272) pp. 161-164.

[4] R.P. Stratford, "Harmonic Pollution on Power Systems - A Change in Philosophy," IEEE Trans. on Industry Applications, Vol. IA-16, No. 5, 1980, pp. 617-623.

[5] R.L. Smith, Jr., and R.P. Stratford, "Power System Harmonics Effects from Adjustable-Speed Drives," IEEE Trans. on Industry Applications, Vol. IA-20, No. 4, 1984, pp. 973-977.

[6] A. Kloss, "A Basic Guide to Power Electronics," John Wiley & Sons Ltd., 1984, Chapter 9 "Harmonics in the Three Phase Bridge Converter."

[7] B. Delfino, G.B. Denegri, F. Profumo and L. Valfre, "Analysis of Abnormal Harmonics in Converter Fed D.C. Motors," IEE Conf. Publ. 234, 1984, pp. 171-174.

[8] A. Kloss "Harmonics Produced by Static Converters under Transient Conditions," IEE Conf. Publ. 210, 1982, pp. 111-115.

[9] N.B. Rowe, "The Summation of Randomly-Varying Phasors or Vectors with Particular Reference to Harmonic Levels," IEE Conf. Publ. 110, pp. 177-181.

[10] R.D. Kendon and P. Whitaker, "Assessment of Combined Harmonic Distortion from a Number of Sources-Work Required," IEE Conf. Publ. 210, 1982, pp. 142-147.

[11] D. Roye, R. Perret, G. Champenois and H. Le-Huy, "Operation and Control of Thyristor Converters under Unbalanced Supply Conditions," IEEE-IAS Annual Conf. Recond, 1986, pp. 763-768.

[12] Albert Kloss, "A Basic Guide to Power Electronics," John Wiley & Sons Ltd., 1984, Chapter 10 - Fault Conditions in the Three-Phase Bridge, pp. 130-143.

[13] D.A. Jarc and R.G. Schieman, "Power Line Considerations for Variable Frequency Drives," IEEE-IAS Annual Conf. Record, 1985, pp. 55-60.

[14] A. Ludbrook, "Harmonic Filters for Notch Reduction," IEEE-IAS Annual Conf. Record, 1986, pp. 1043-1047.

[15] Rusong Wu, S.B. Dewan and G.R. Slemon, "A PWM AC to DC Converter with Fixed Switching Frequency," IEEE-IAS Annual Conf. Record, 1988, pp. 706-711.

[16] M. Hombu, S. Ueda and A. Ueda, "A Current Source GTO Inverter with Sinusoidal Inputs and Outputs," IEEE-IAS Annual Conf. Record, 1985, pp. 1033-1039.

[17] S. Fukuda and H. Hasegawa, "Current Source Rectifier/Inverter System with Sinusoidal Currents," IEEE-IAS Annual Conf. Record, 1988, pp. 909-914.

[18] D.A. Gonzalez and J.C. McCall, "Design of Filters to Reduce Harmonic Distortion in Industrial Power Systems," IEEE-IAS Annual Conf. Record, 1985, pp. 361-370.

[19] Z.S. Bialkiewicz, "Reducing of Harmonics in MV Networks with LC-Filters," IEE International Conf. on Sources & Effects of Power System Disturbances, 1974, conv. Publ.110, pp. 151-155.

[20] R.W.Y. Cheung, "A Generalized Basis-Transformed State-Space Approach for Computer-Aided Analysis and Design of Power Conditioning System," Ph.D. Thesis, University of Toronto, 1986.

[21] M. Kohata etal., "A Novel Compensator using Static Induction Thyristors for Reactive Power and Harmonics," IEEE-IAS Annual Conf.Record, 1988, pp. 843-849.

[22] H. Akagi, Y. Kanazawa and A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components," IEEE Trans. on Industry Applications, Vol.IA-20, No. 3, 1984, pp. 625-630.

[23] H. Akagi, Y. Tsukamoto and A. Nabae, "Analysis and Design of an Active Power Filter using Quad-Series Voltage Source PWM Converters," IEEE-IAS Annual Conf. Record, 1988, pp. 867-873.

[24] F.Z. Peng, H. Akagi and A. Nabae, "A New Approach to Harmonic Compensation in Power Systems," IEEE-IAS Annual Conf. Record, 1988, pp. 874-880.

[25] Masatashi Takeda, etal., "Harmonic Current Compensation with Active Filter," IEEE-IAS Annual Conf. Record, 1987, pp. 800-815.

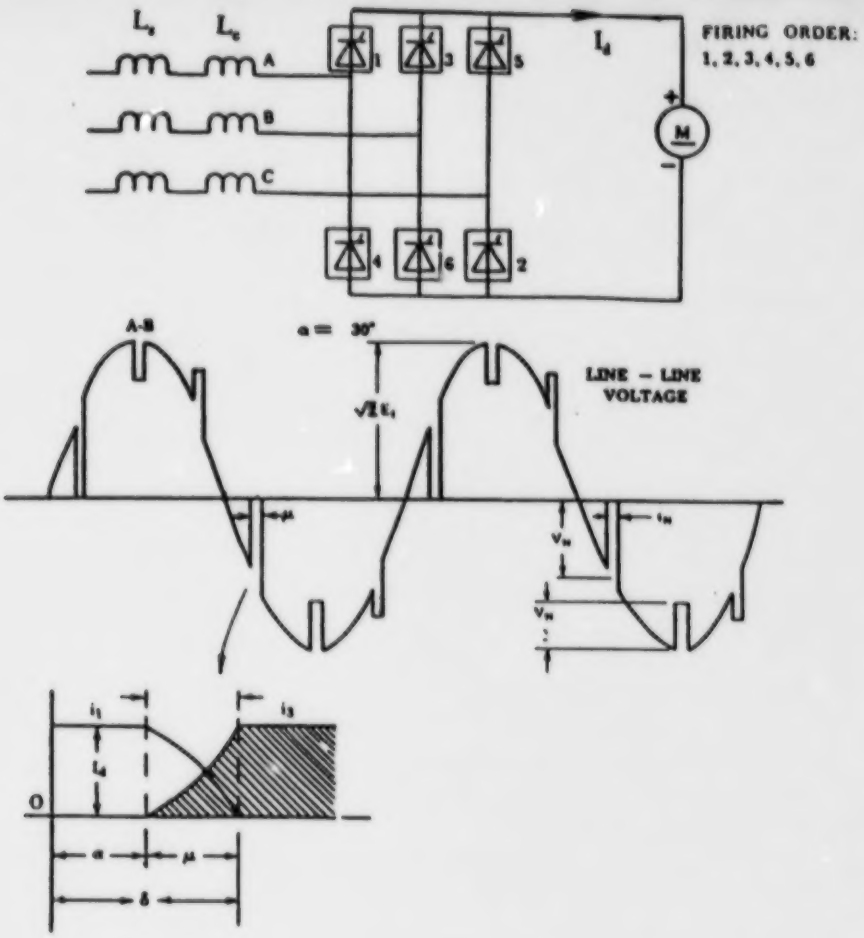


Figure 1.1 Voltage Notches at Converter Input.

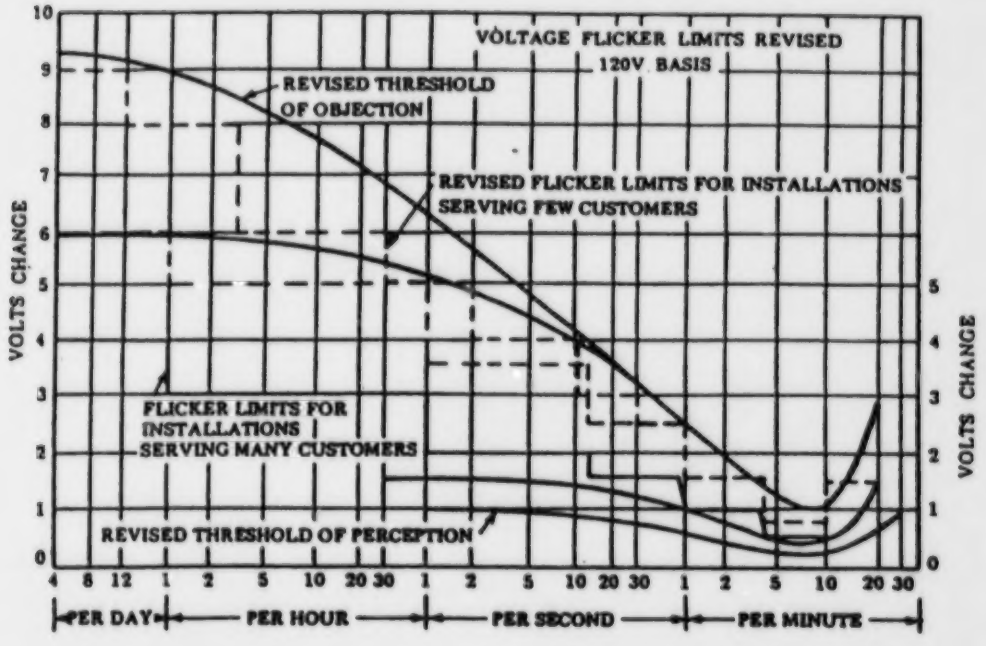


Figure 1.2 Maximum Permissible Voltage Fluctuation.

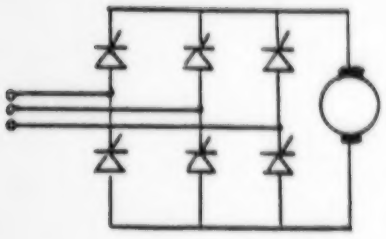


Figure 2.1 AC/DC Converter Drive.

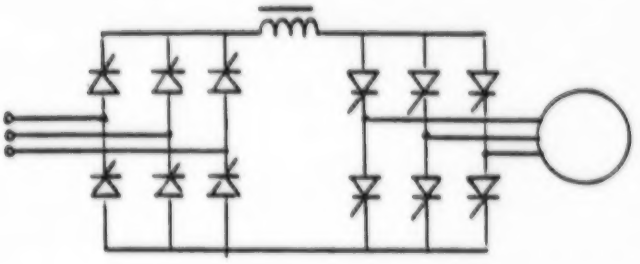


Figure 2.2 Square-Wave / PWM CSI Drive.

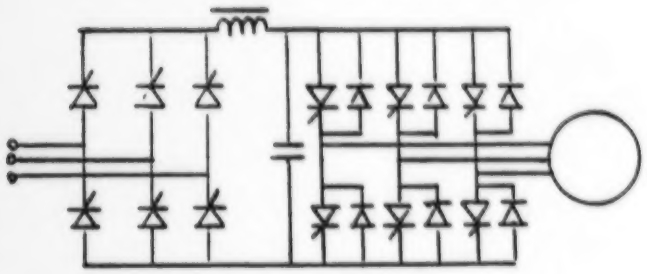


Figure 2.3 Square-Wave / PWM VSI Drive.

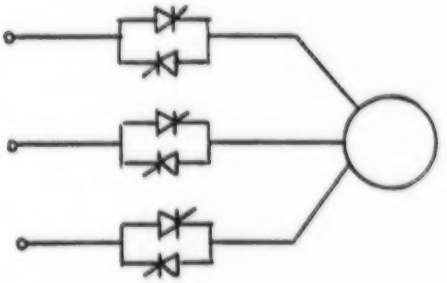


Figure 2.4 AC Phase-Controlled Drive.

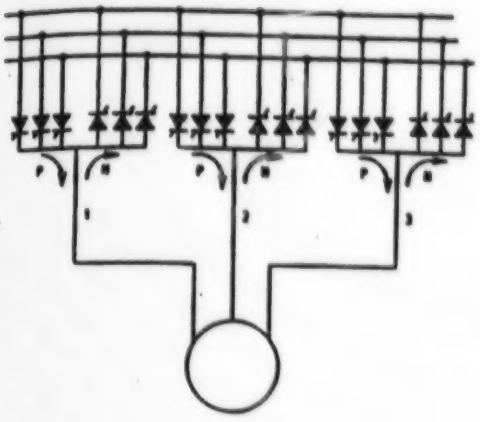


Figure 2.5 Cycloconverter Drive.

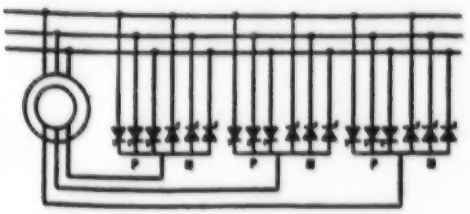


Figure 2.6 Scherbulus Drive.

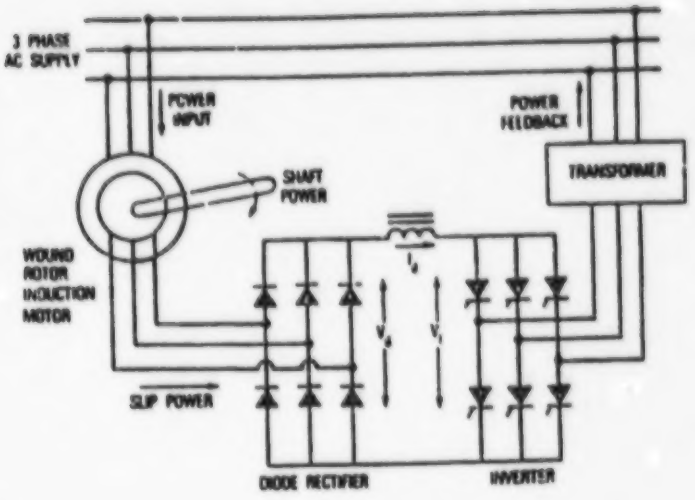


Figure 2.7 Kramer Slip-Energy-Recovery Drive.

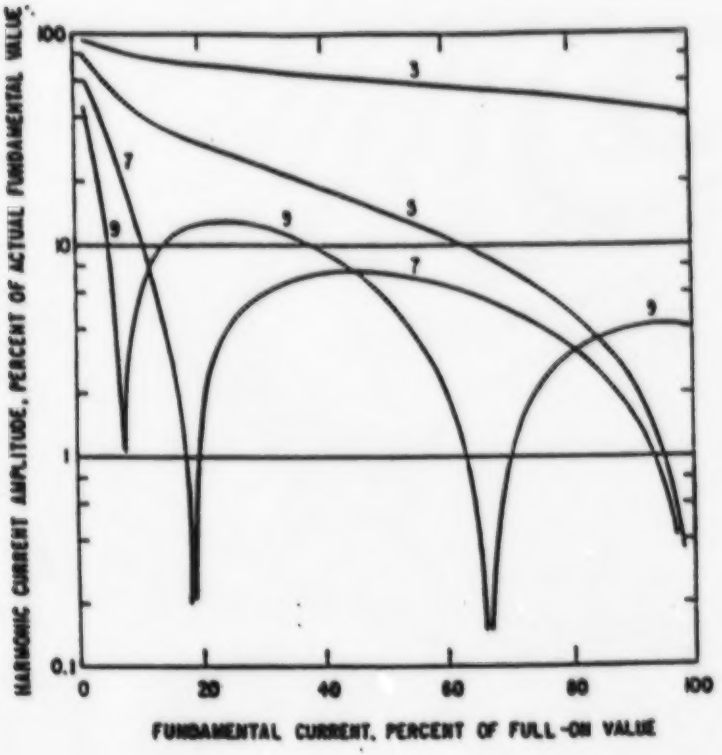


Figure 2.8 Current Harmonics of Phase-Controlled Drive.
(Curves are numbered with the order of harmonics)

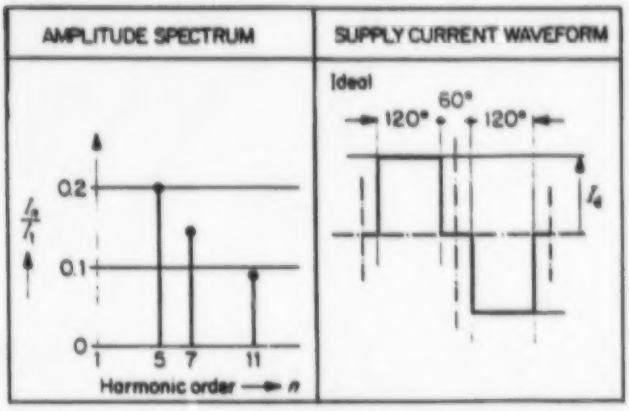


Figure 2.9(a) **Harmonic Spectrum of Symmetrical Line Currents.**

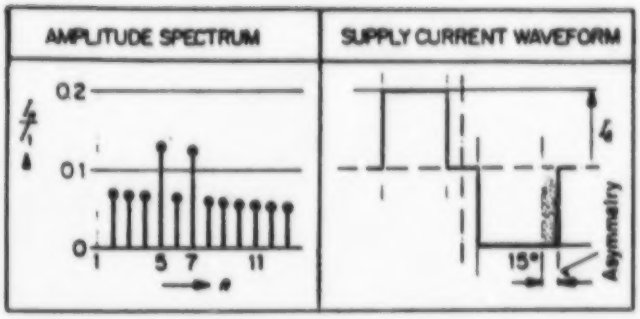


Figure 2.9(b) **Harmonic Spectrum of Non-Symmetrical Line Currents.**

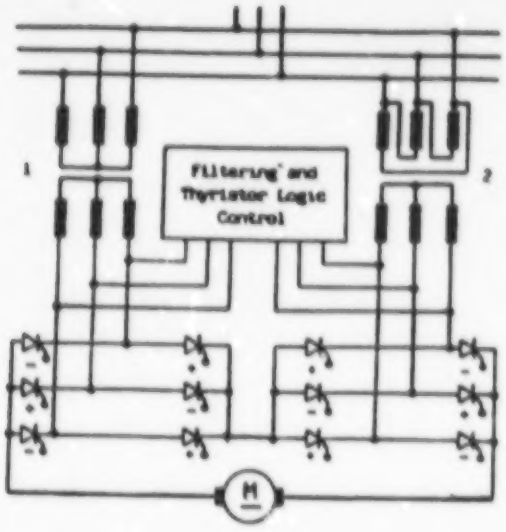


Figure 2.10(a) **Schematic circuit of 12-pulse dc motor drive**

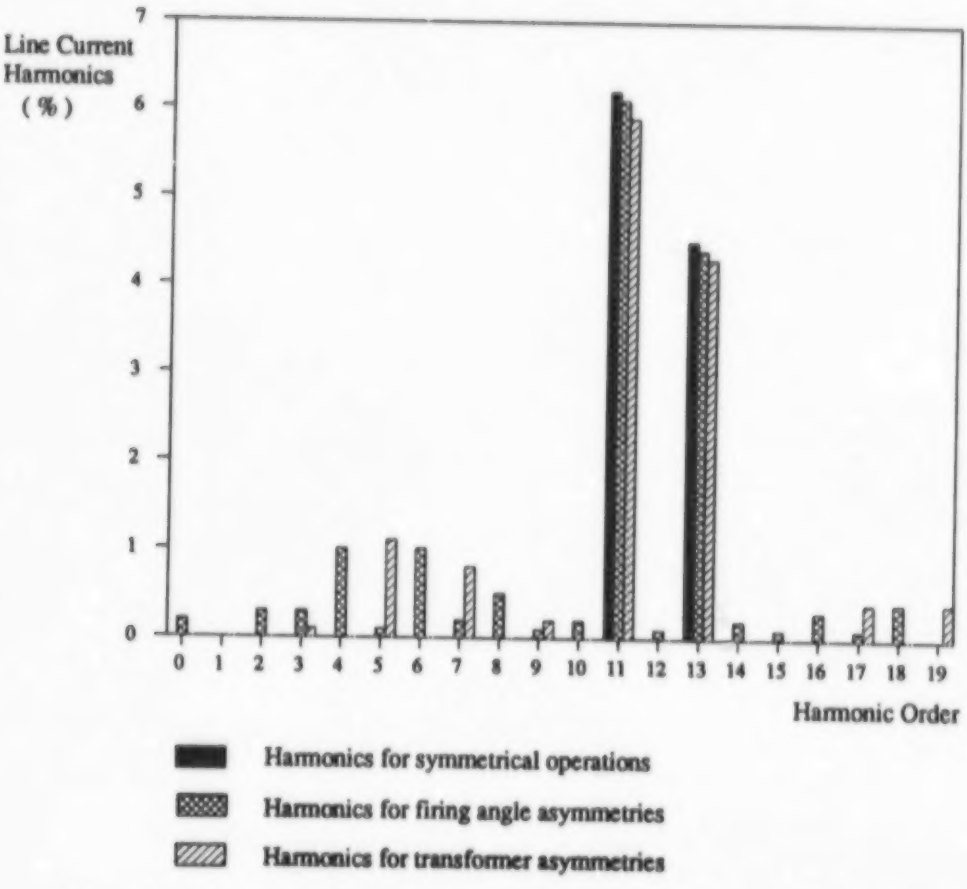


Figure 2.10(b) **Current harmonics from the drive under symmetrical and non-symmetrical operating conditions.**

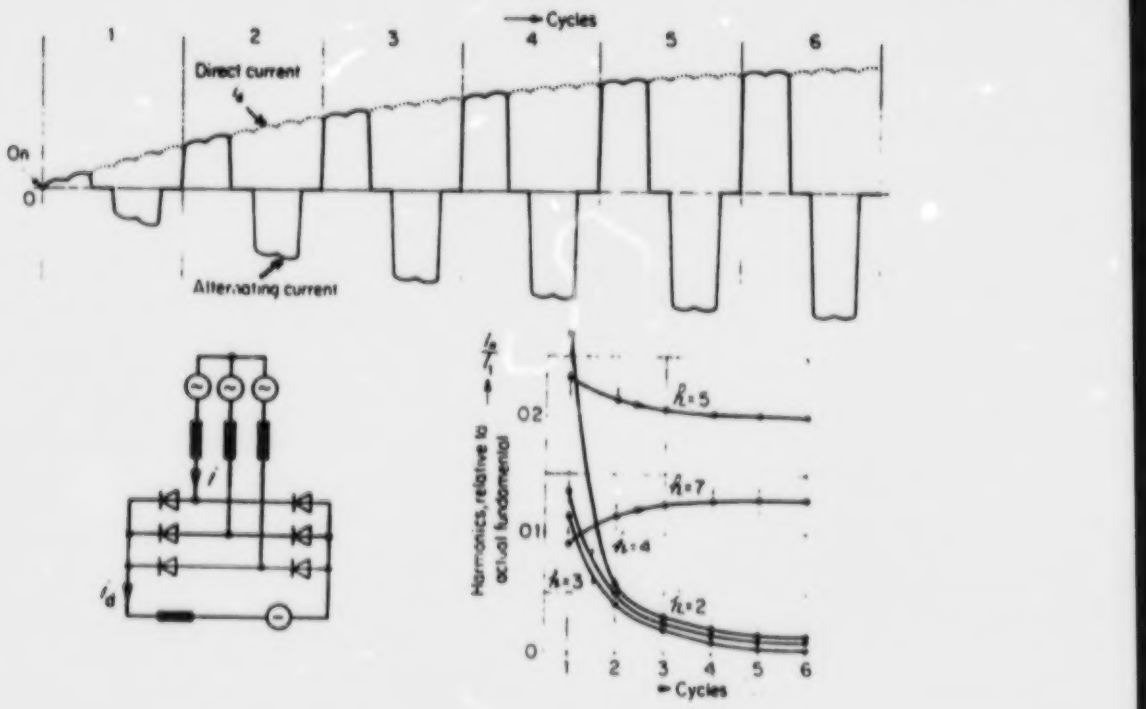


Figure 2.11 **Variation of harmonics from AC/DC converter during the transient period of load-current rise.**

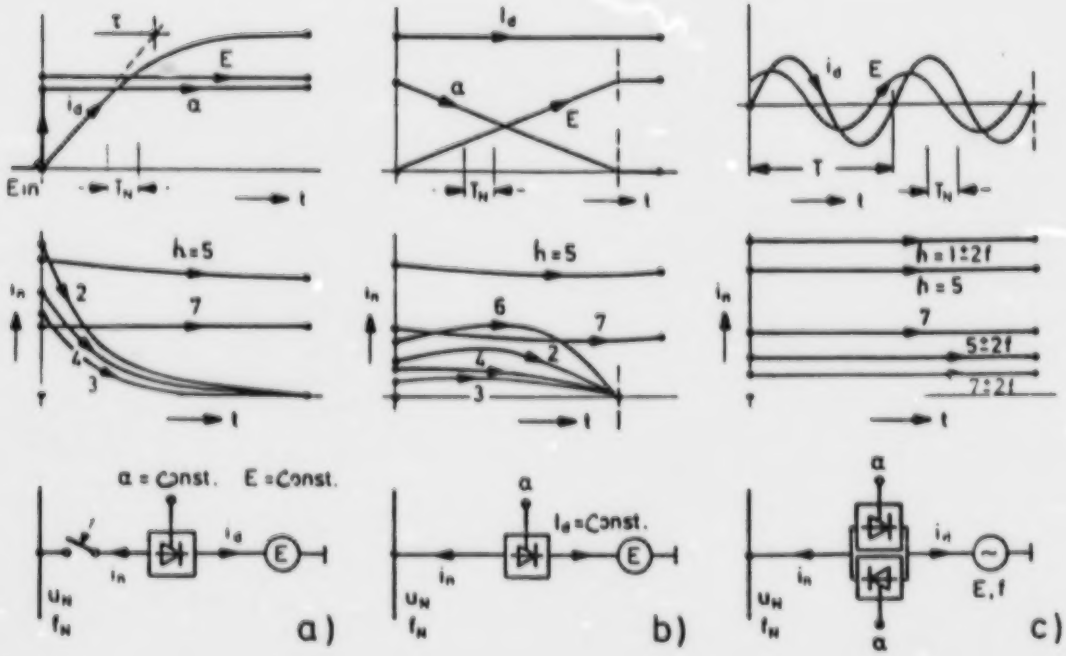


Figure 2.12 **Harmonic variation caused by converters under the circuit conditions: a) Constant E and α, b) Constant i_d, c) Cycloconverter.**

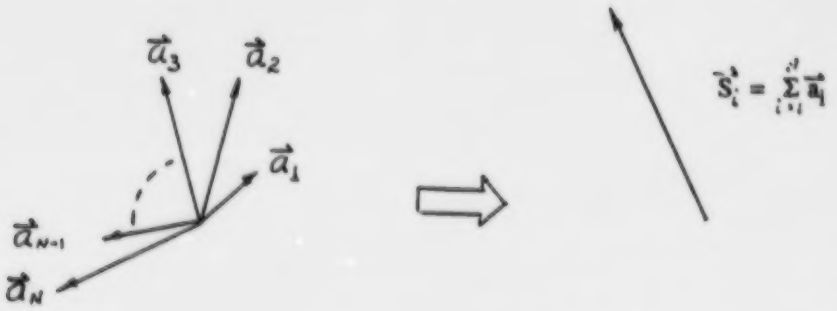


Figure 2.13 **Vector summation of N harmonic phasors.**

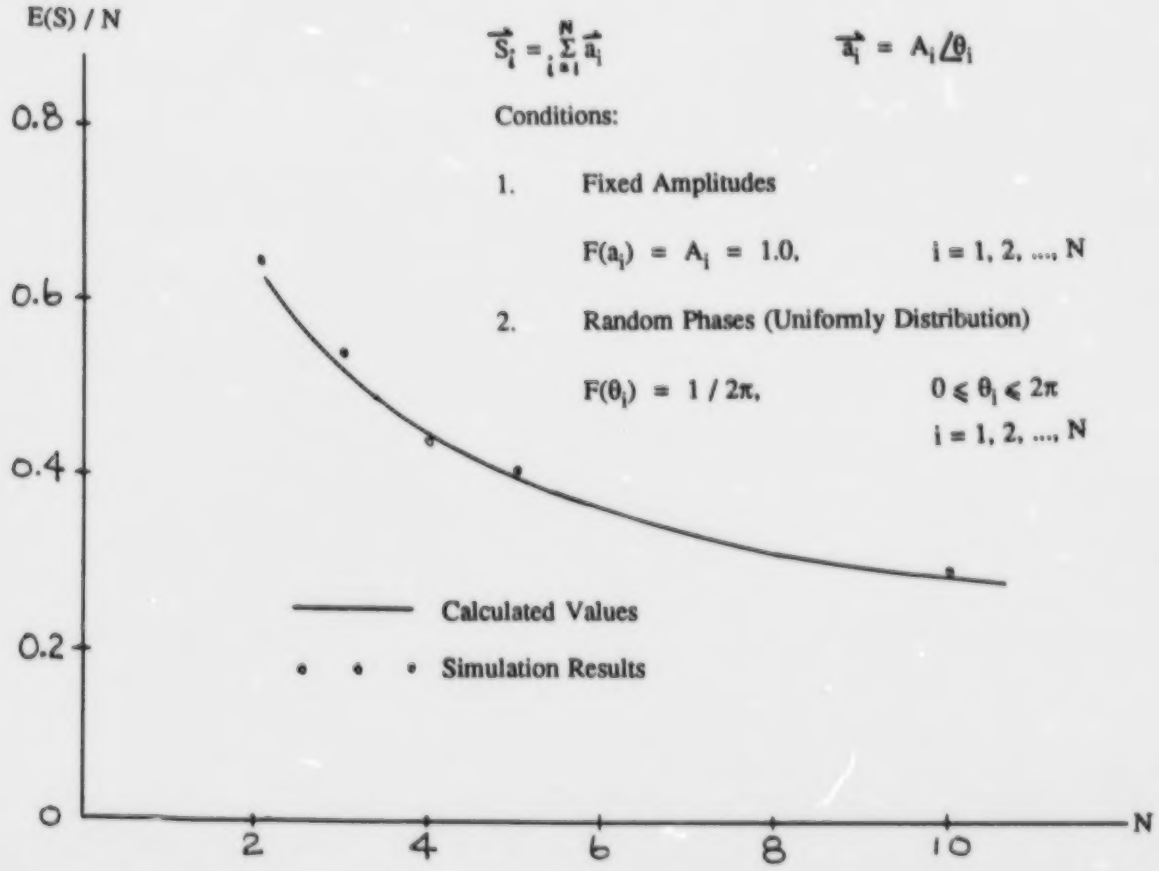


Figure 2.14 **Mean expected value of N phasors with fixed amplitudes and random phases.**

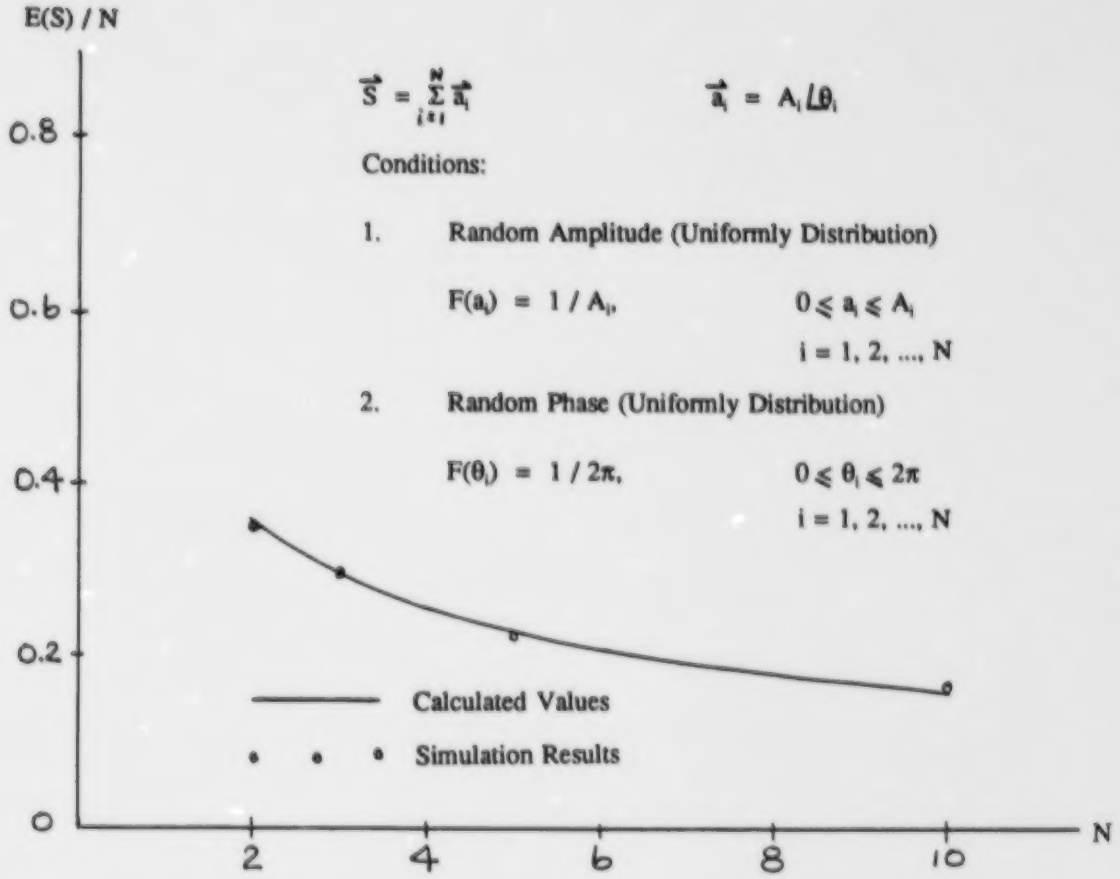


Figure 2.15 **Mean expected value of N phasors with random amplitudes and random phases.**

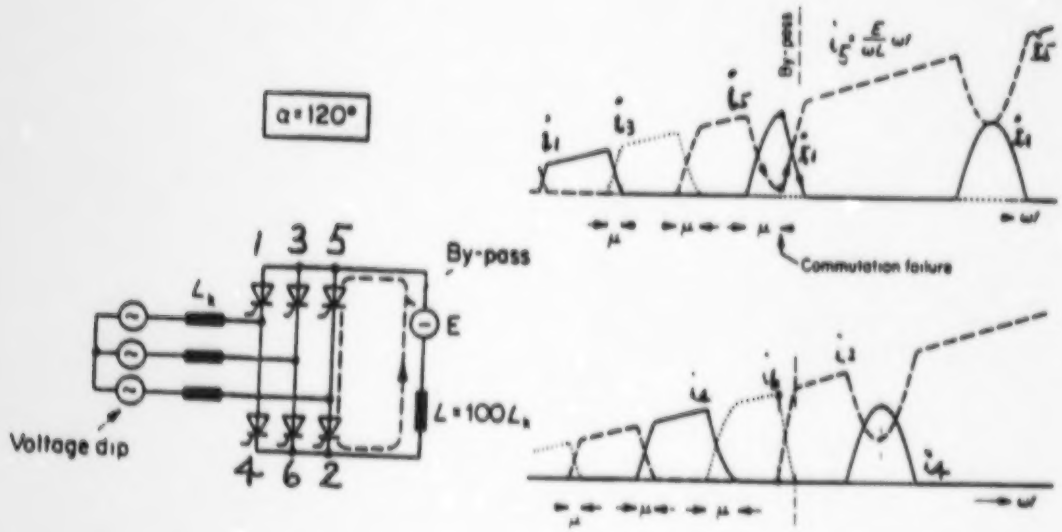


Figure 3.1 **A commutation failure due to a supply-voltage dip, resulting a short circuit through two thyristors for $\alpha = 120°$.**

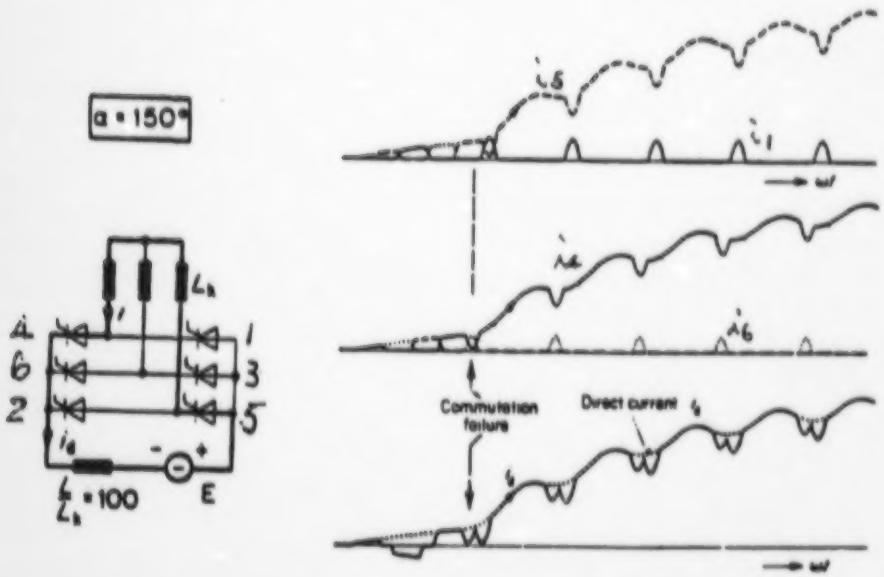


Figure 3.2 **A commutation failure due to a supply-voltage dip, resulting in a short circuit through the three-phase supply system.**

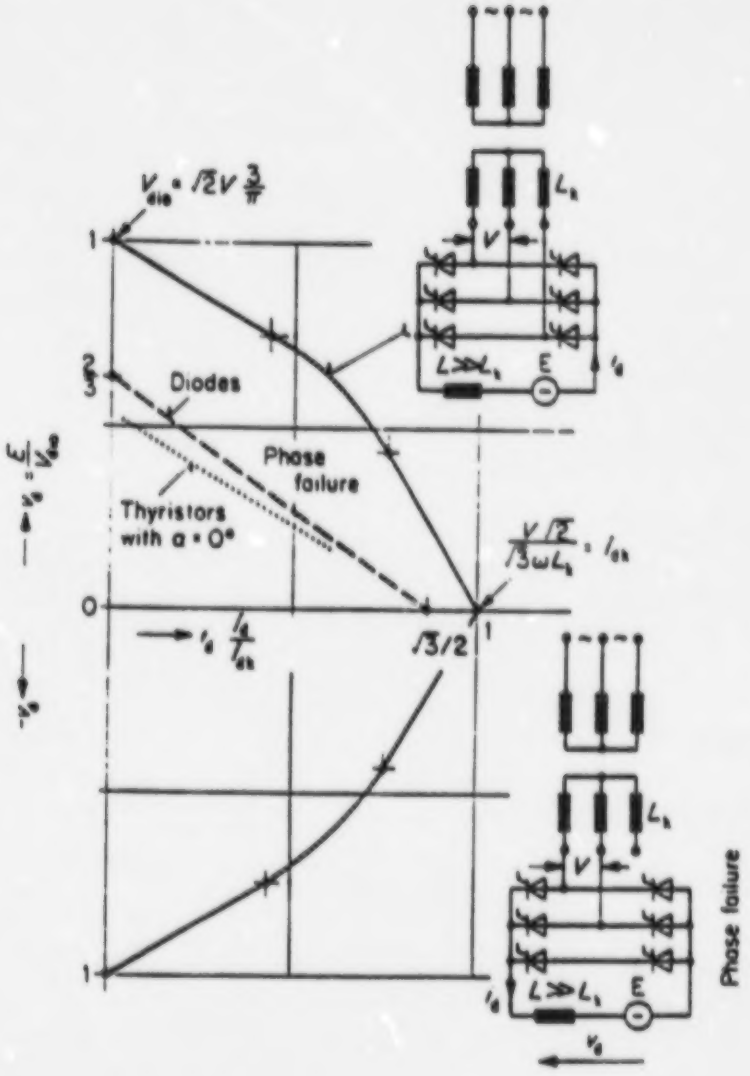
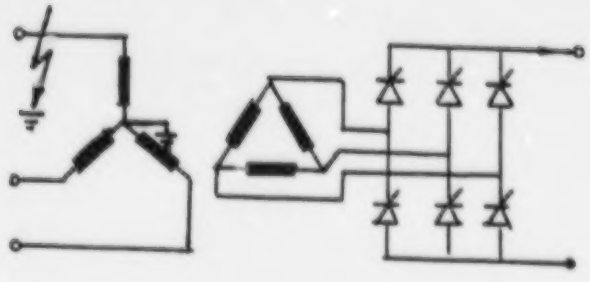
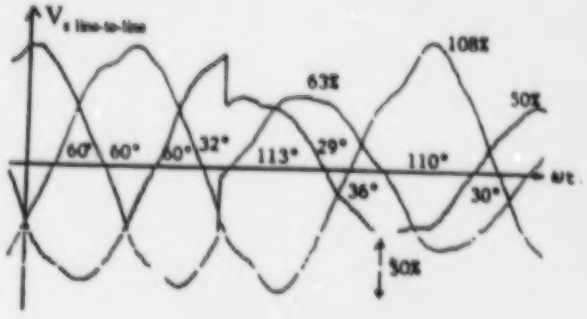


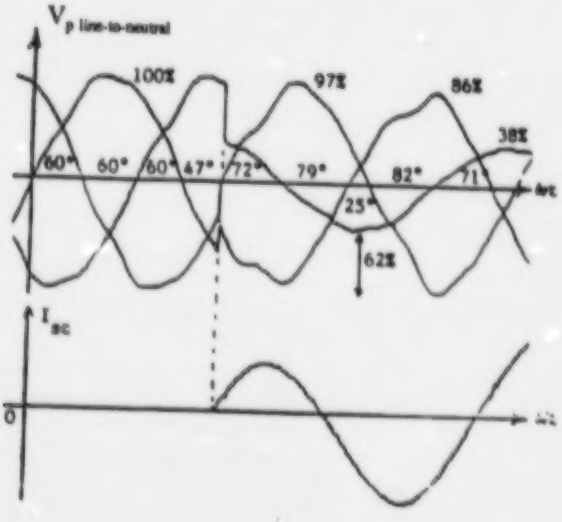
Figure 3.3 **A converter operated in a limited two-pulse mode when one supply phase is lost.**



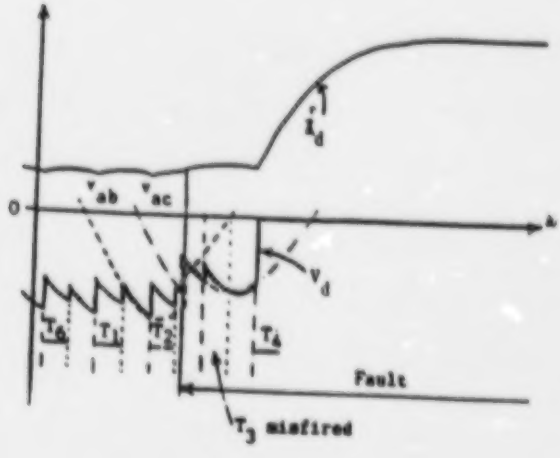
a) Converter circuit



c) Transformer secondary voltages



b) Transformer primary voltage and fault current



d) DC voltage and current

Figure 3.4 **The performance of 6-pulse converter during a line-to-ground fault on the supply line, resulting a line-to-line short circuit at the converter input.**

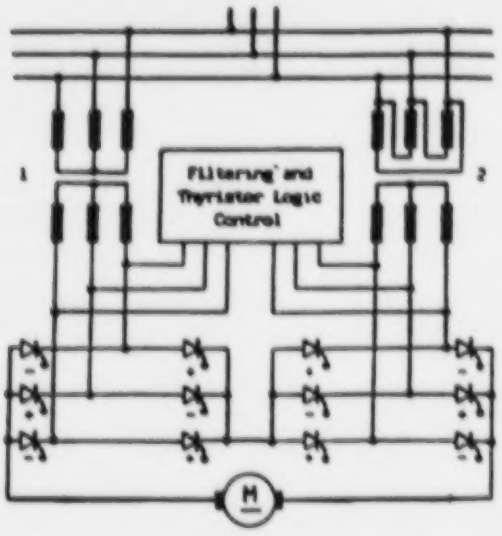


Figure 3.5(a) **Schematic circuit of 12-pulse dc motor drive**

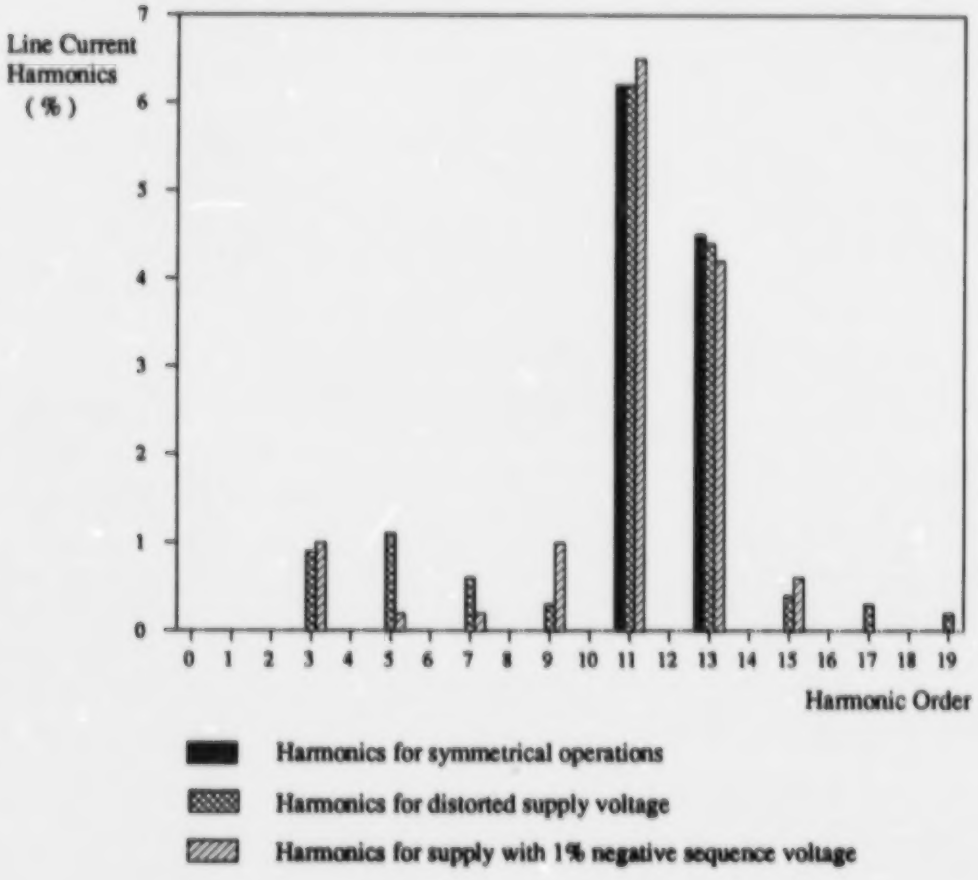


Figure 3.5(b) **Current harmonics from the drive under symmetrical and unbalanced supply.**

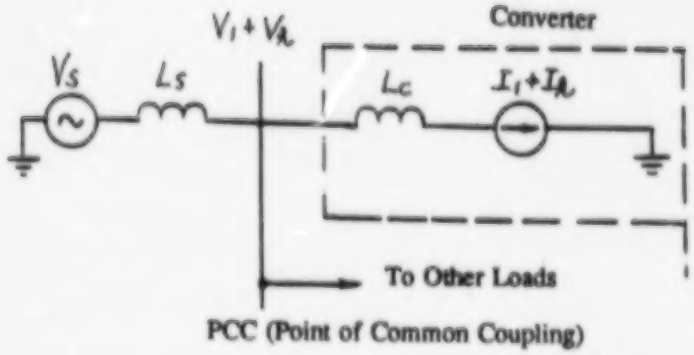


Figure 4.1 **A variable speed drive modelled as a harmonic-current generator.**

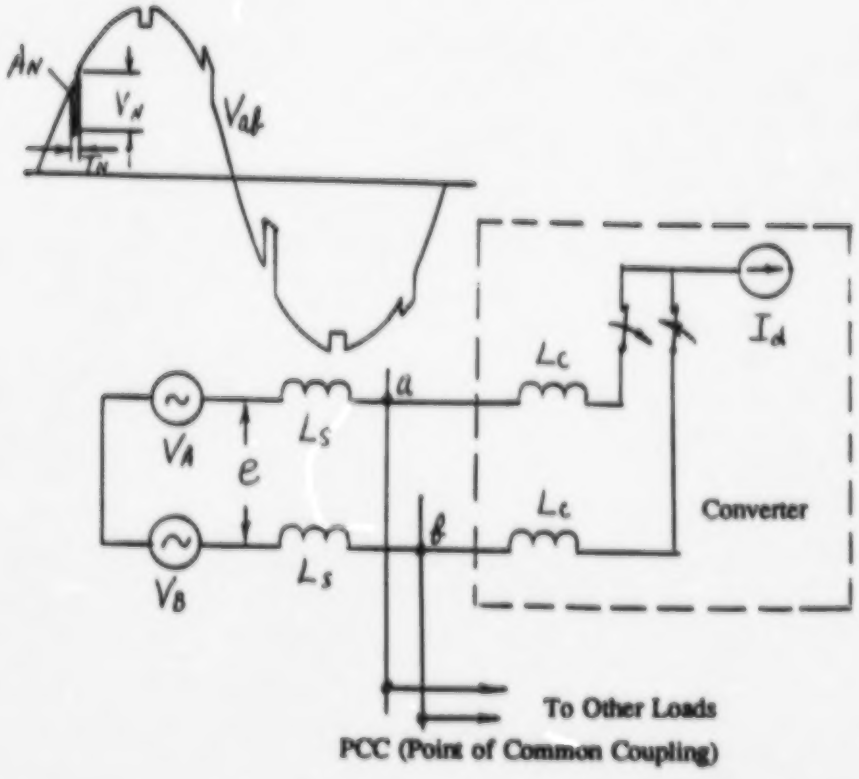


Figure 4.2 **An equivalent circuit for illustrating the mechanism of voltage notch formation.**

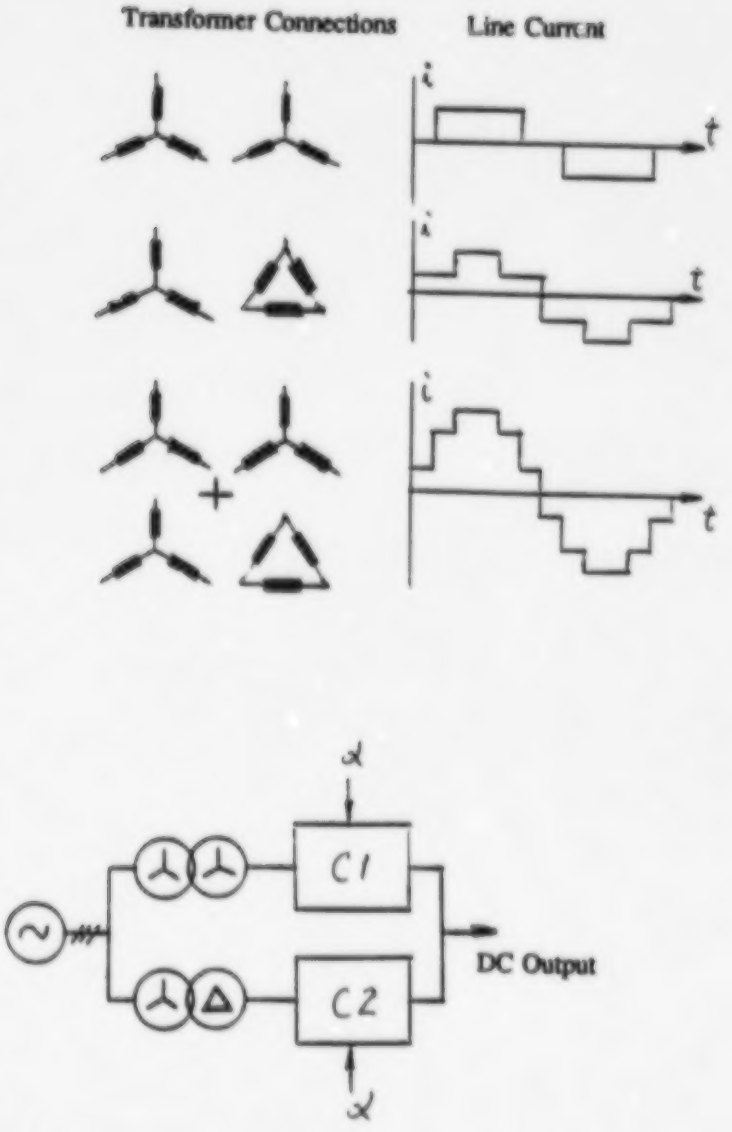


Figure 4.3 **A multiphasing system from two 6-pulse converters.**

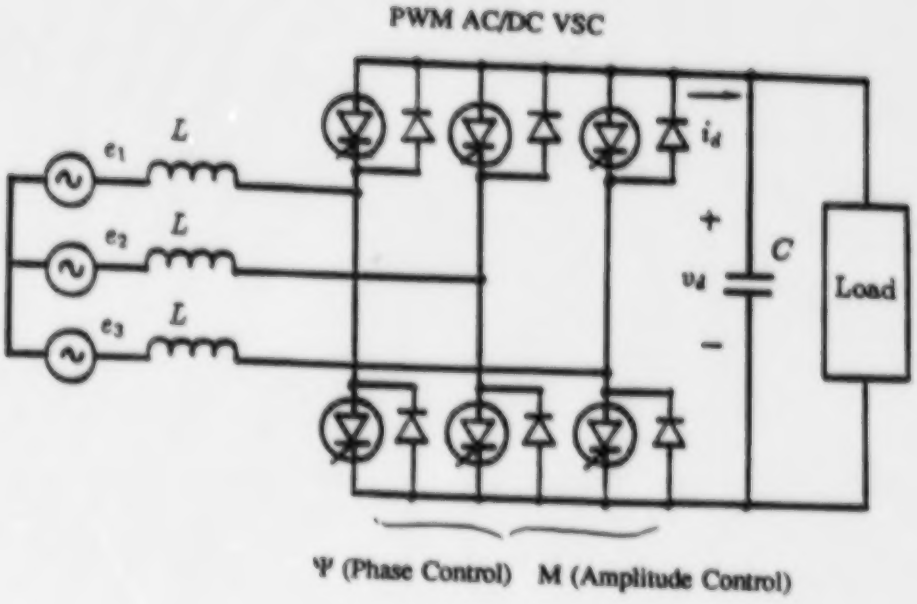


Figure 4.4(a) **A PWM AC/DC voltage-output converter for machine drives.**

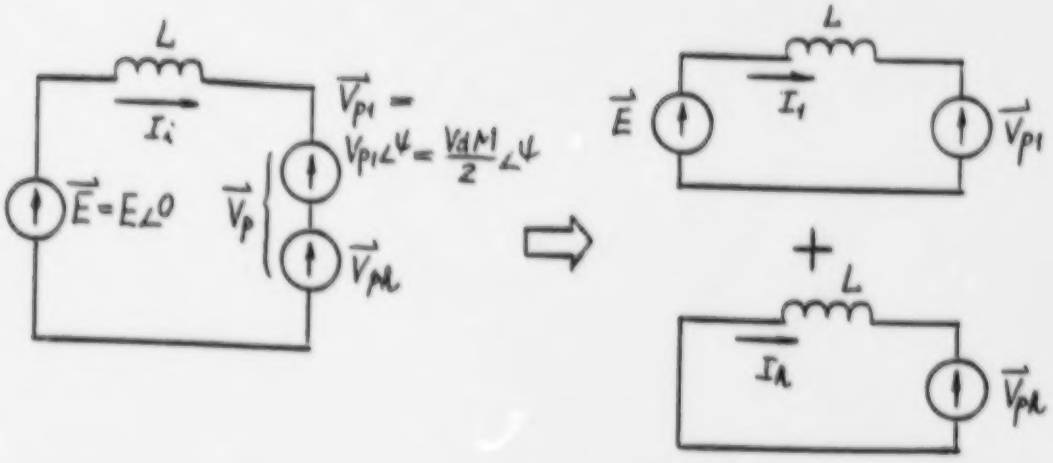


Figure 4.4(b) **A single-phase representation of PWM AC/DC voltage-output converter.**

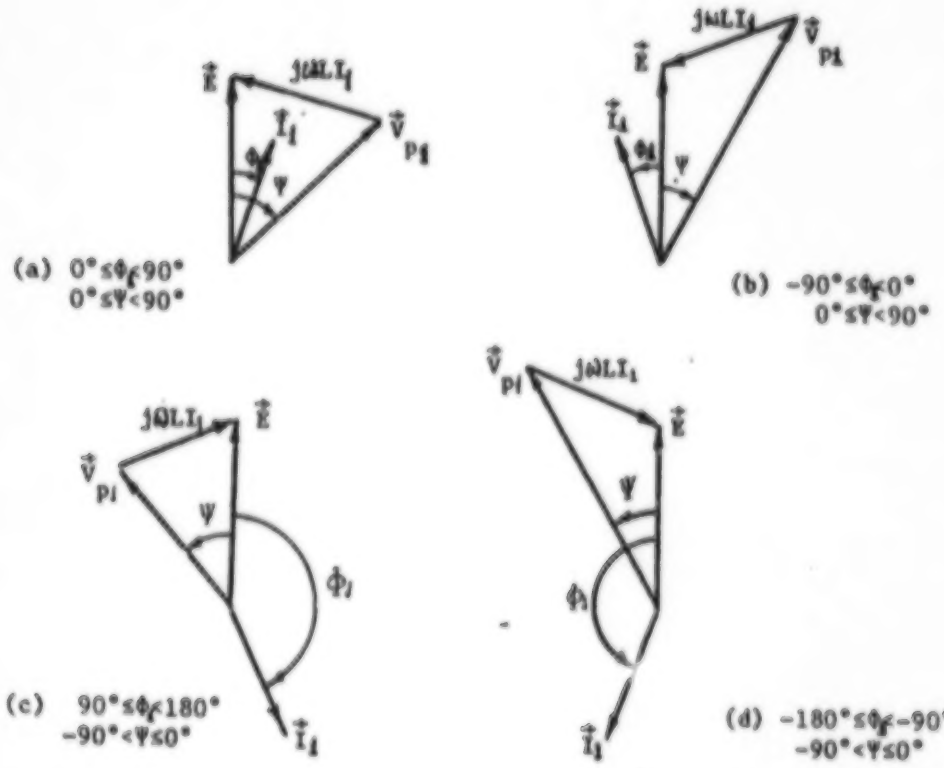


Figure 4.5 **Phasor diagrams of fundamental voltages and currents in a PWM voltage-output converter.**

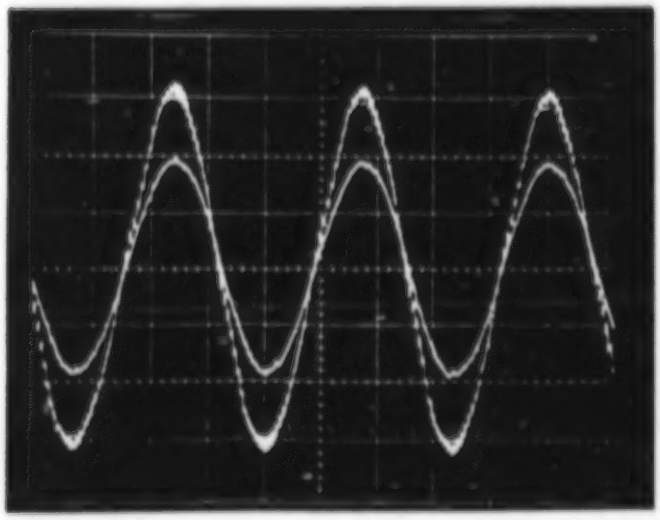


Figure 4.6 **Waveforms of line current and phase voltage in a PWM voltage-output converter.**

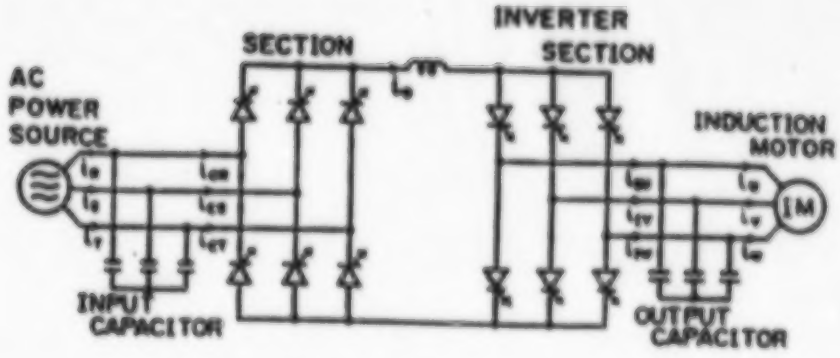


Figure 4.7 A PWM AC/DC current-output converter for CSI drives.

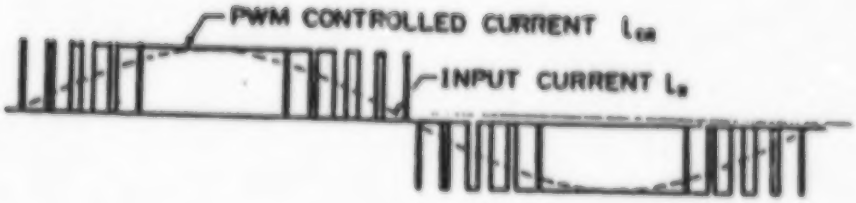


Figure 4.8 A chopped waveform at the input of a PWM current-output converter.

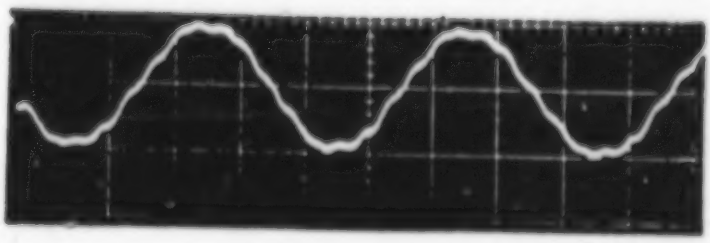
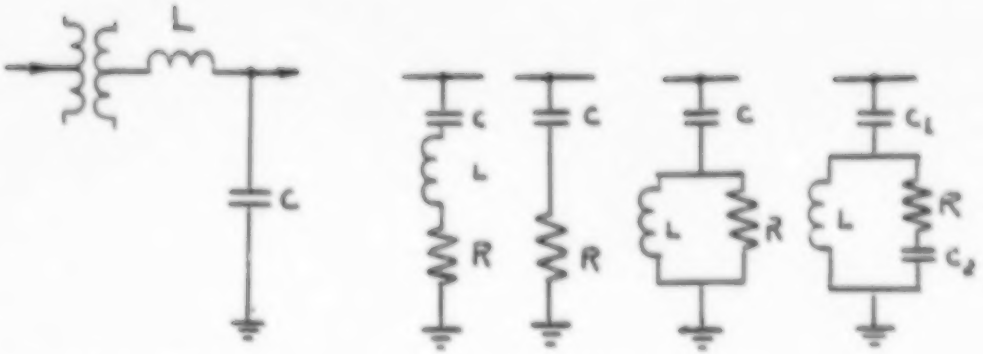


Figure 4.9 The input supply current filtered by input capacitors.



(a) Series Filter (b) Shunt Filters

Figure 4.10 **Basic configurations of series and shunt passive power filters.**

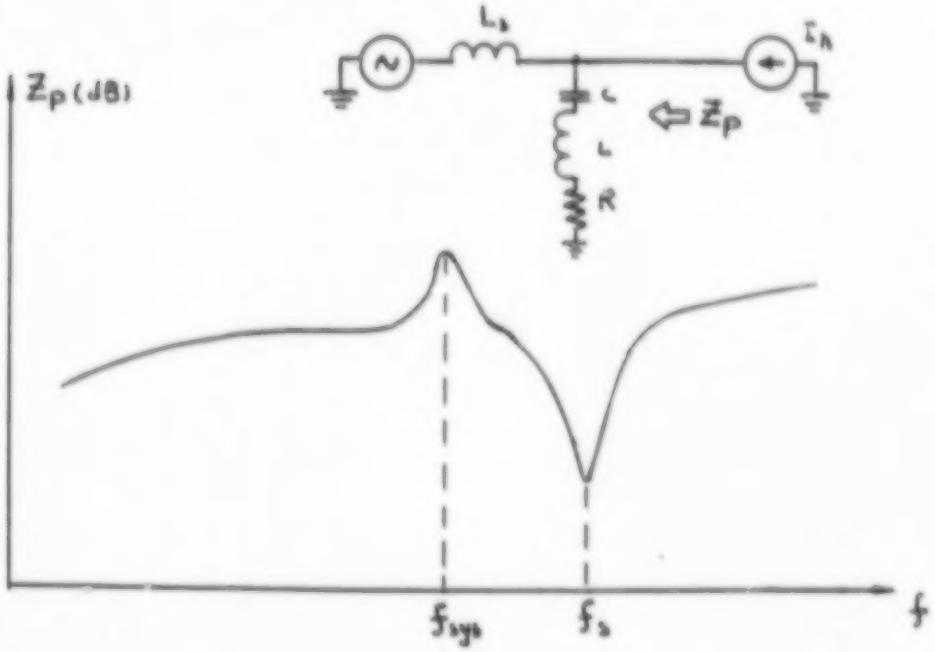


Figure 4.11 **Frequency response of a combined impedance for power filter and supply system.**

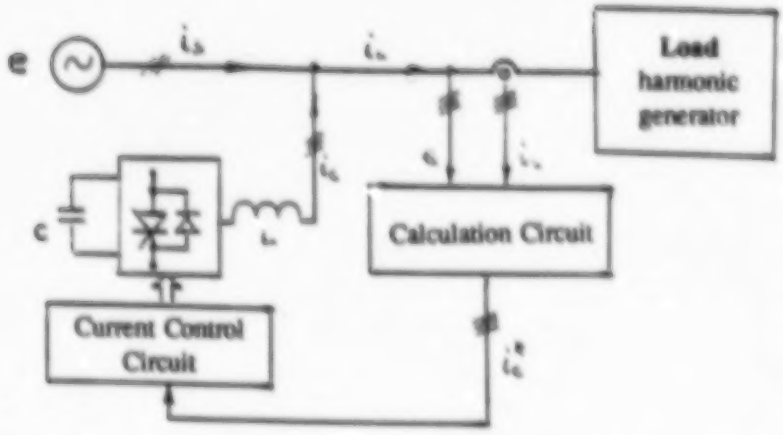


Figure 4.12 A simplified block diagram of active power filter.

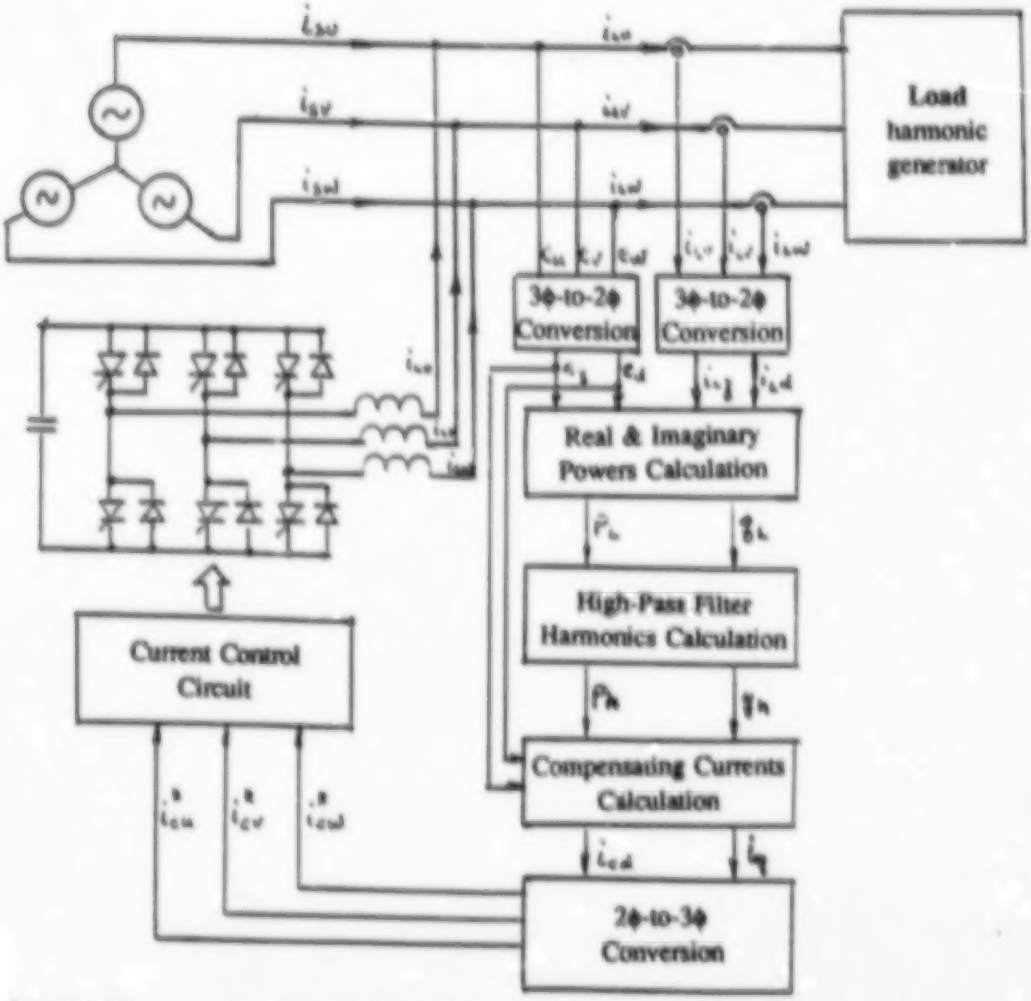


Figure 4.13 A system configuration of active power filter with control blocks.

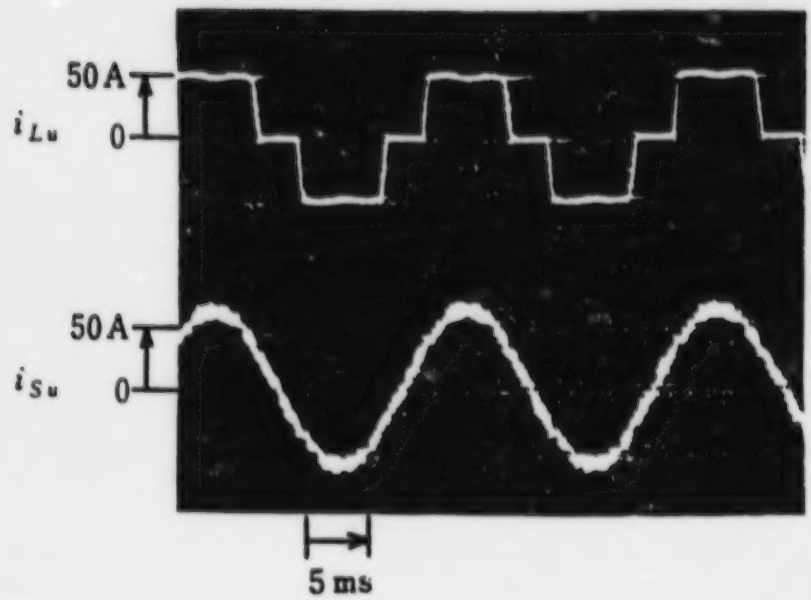


Figure 4.14 **Experimental waveforms of the load current and input line current.**